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(54) OVERVOLTAGE PROTECTION DEVICE MODULES AND SHEATH BONDING SYSTEMS INCLUDING SAME

(57) A surge protective device includes a link box including a plurality of connectors and one or more sheath voltage limiter (SVL) circuits. The plurality of connectors are configured to interface with a plurality of cables, each of the plurality of cables including an inner conductor and a conductive sheath surrounding the inner conductor. The one or more sheath voltage limiter (SVL) circuits is/are configured for connection to the plurality of terminals and an electrical ground, the one or more SVL circuits having a residual voltage that is less than a minimum induced voltage generated during a power frequency fault on one or more of the plurality of conductive sheaths, but greater than a nominal operating voltage on the one or more of the plurality of conductive sheaths.

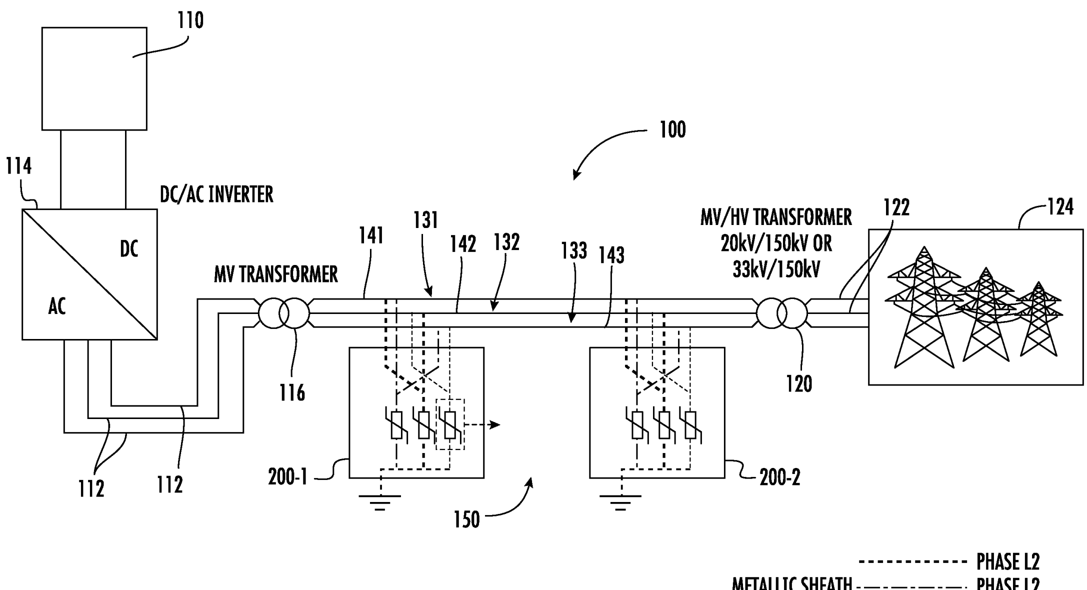

FIG. 1

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Description

Field of the Invention

[0001] The present invention relates to overvoltage protection devices and, more particularly, to overvoltage protection devices including varistors.

Background of the Invention

[0002] In some power generation and transmission systems, electricity is transmitted at medium voltage (in the range of from 5kV to 36kV) over medium voltage (MV) cables. For example, power from power sources such as photovoltaic parks and wind turbines may be transmitted to a utility substation over MV cables. The MV cables include a main electrical conductor, an insulation layer surrounding the main conductor with two dielectric layers inside and outside of the insulation layer, an electrically conductive metal shield/ sheath surrounding the insulation layer, and a jacket surrounding the sheath.

[0003] In such applications, induced sheath voltages and induced circulating currents in the sheath can cause problems. To mitigate these effects, cable sheath bonding or earthing techniques are employed. These sheath bonding techniques include single-point bonding, solid-bonding, and cross-bonding.

[0004] In solid bonding, each cable sheath is solidly connected to earth ground at both ends of the sheath. Substantial circulating currents may be induced in the sheath by the current conducted through the main conductor of the MV cable, resulting in significant power losses and heat generation.

[0005] In single-point bonding, each cable sheath is solidly earth grounded at a first end and the opposing second end of the sheath is isolated from ground. The second end is typically connected to a sheath voltage limiter (SVL) that is connected to ground to provide surge protection from induced lightning events (mainly 8/20us surge current waveform). The SVL typically includes a varistor-based surge arrestor that shorts the sheath to ground in response to a sufficient overvoltage (corresponding surge event) on the sheath. The connections and SVLs may be provided in a link box to which the sheaths are connected via connecting cables.

[0006] In cross-bonding, each sheath of a major section of cable is severed or sectionalized into three minor (as an example, it could be less on more depending on the cross-bonding scheme selected form the engineer) sections. The outer ends of the minor sections or outer ends of the major section of the cable are solidly earth grounded. The inner ends of the minor sections are cross-connected between sheaths. The cross-connected ends are typically connected to an SVL that is connected to ground to provide TOV protection. The cross-connections and SVLs may be performed in a link box. The sheaths are connected to the cross-connections via connecting cables. When the minor sections have equal lengths, the induced sheath voltages in the minor sections are equal in magnitude, but 120° out of phase with each other. When the sheaths are cross-connected, each sheath circuit contains one section from each phase, such that the total voltage in each circuit sums to approximately zero. By solidly bonding the sheaths at the ends of the major section of cable, the net voltage in the loop will be approximately zero and the circulating currents will be zero in an idealized case.

Summary

[0007] According to some embodiments, a sheath bonding system includes a link box including a plurality of connectors and one or more sheath voltage limiter (SVL) circuits. The plurality of connectors are configured to interface with a plurality of cables, each of the plurality of cables including an inner conductor and a conductive sheath surrounding the inner conductor. The one or more sheath voltage limiter (SVL) circuits is/are configured for connection to the plurality of terminals and an electrical ground, the one or more SVL circuits having a residual voltage that is less than a minimum induced voltage generated during a power frequency fault on one or more of the plurality of conductive sheaths, but greater than a nominal operating voltage on the one or more of the plurality of conductive sheaths.

[0008] According to some embodiments, the one or more SVL circuits has a maximum continuous operating voltage that is less than the minimum induced voltage generated during the power frequency fault on the one or more of the plurality of cables, but greater than the nominal operating voltage on the one or more of the plurality of cables.

[0009] In some embodiments, the maximum continuous operating voltage is about 10% greater than the nominal operating voltage on the one or more of the plurality of conductive sheaths.

[0010] According to some embodiments, the plurality of connectors are configured to connect the conductive sheaths of the respective ones of the plurality of cables to each other in a cross-connect arrangement.

[0011] In some embodiments, the plurality of connectors are configured to connect the conductive sheaths to the one or more SVL circuits in a single point bonding arrangement.

[0012] According to some embodiments, the plurality of cables are configured to operate as medium voltage power cables.

[0013] In some embodiments, medium voltage is in a range of about 5 kV to about 36 kV.

[0014] According to some embodiments, the one or more SVL circuits each has a withstand energy characteristic associated therewith, and each of the SVL circuits is configured to non-destructively process a power frequency fault or a transient overvoltage event when the power frequency fault or the transient overvoltage event does not exceed the withstand energy characteristic of the respective SVL circuit.

[0015] In some embodiments, the withstand characteristic of each of the one or more SVL circuits is 33 kA applied in a 10/350μs profile.

[0016] According to some embodiments, the plurality of cables are arranged in a trefoil formation.

[0017] According to some embodiments, the one or more SVL circuits comprise one or more varistors.

[0018] According to some embodiments, each of the one or more varistors includes a first fail-safe system and a second fail-safe system.

[0019] In some embodiments, the first fail-safe system is configured to arc in response to current received through the respective varistor.

[0020] In some embodiments, the second fail-safe system is configured to operate in response to heat generated by current received through the respective varistor.

[0021] In some embodiments, the second fail-safe system comprises a meltable member.

[0022] According to some embodiments, the minimum induced voltage generated during a power frequency fault is about 500 - 1000 volts.

[0023] In some embodiments, the residual voltage is in a range of about 80% - 90% of the minimum induced voltage generated during the power frequency fault.

[0024] According to some embodiments, the plurality of cables are configured to operate as high voltage power cables. In some embodiments, high voltage is in a range of about 150 kV to about 400 kV.

[0025] According to some embodiments, a sheath bonding system, comprises: a plurality of cables, each of the plurality of cables including an inner conductor and a conductive sheath surrounding the inner conductor; and one or more sheath voltage limiter (SVL) circuits configured for connection to the plurality of cables and an electrical ground, the one or more SVL circuits having a residual voltage that is less than a minimum induced voltage generated during a power frequency fault on one or more of the plurality of conductive sheaths, but greater than a nominal operating voltage on the one or more of the plurality of conductive sheaths.

[0026] In some embodiments, the one or more SVL circuits has a maximum continuous operating voltage that is less than the minimum induced voltage generated during the power frequency fault on the one or more of the plurality of cables, but greater than the nominal operating voltage on the one or more of the plurality of cables.

[0027] In some embodiments, the maximum continuous operating voltage is about 10% greater than the nominal operating voltage on the one or more of the plurality of conductive sheaths.

[0028] In some embodiments, the conductive sheaths of the respective ones of the plurality of cables are connected to each other in a cross-connect arrangement.

[0029] In some embodiments, the conductive sheaths are connected to the one or more SVL circuits in a single point bonding arrangement.

[0030] In some embodiments, the minimum induced voltage generated during a power frequency fault is about 500 - 1000 volts.

[0031] In some embodiments, the residual voltage is in a range of about 80% - 90% of the minimum induced voltage generated during the power frequency fault.

[0032] According to some embodiments, a sheath bonding system comprises: a link box comprising a plurality of terminals and a plurality of connectors connected to the plurality of terminals; a plurality of cables, each of the plurality of cables including an inner conductor and a conductive sheath surrounding the inner conductor; a plurality of linking cables configured to connect the plurality of cables to the plurality of connectors; and one or more sheath voltage limiter (SVL) circuits configured for connection to the plurality of terminals and an electrical ground, the one or more SVL circuits having a residual voltage that is less than a minimum induced voltage generated during a power frequency fault on one or more of the plurality of conductive sheaths, but greater than a nominal operating voltage on the one or more of the plurality of conductive sheaths.

[0033] In some embodiments, the plurality of conductive sheaths are sectionalized into sheath minor sections, the sheath bonding system further comprising: a plurality of cable joints, respective ones of the plurality of cable joints being configured to electrically isolate adjacent ends of the sheath minor sections from one another.

[0034] In some embodiments, the plurality of cable joints are further configured to electrically connect the plurality of linking cables to the sheath minor sections.

[0035] In some embodiments, the plurality of connectors are configured to connect the conductive sheaths of the respective ones of the plurality of cables to each other in a cross-connect arrangement.

[0036] In some embodiments, the plurality of connectors are configured to connect the conductive sheaths to the one or more SVL circuits in a single point bonding arrangement.

[0037] According to some embodiments, a power generation system comprises: an electrical power source; a transmission grid; a plurality of cables configured to couple the electrical power source to the transmission grid, each of the plurality of transmission cables including an inner conductor and a conductive sheath surrounding the inner conductor; and one or more sheath voltage limiter (SVL) circuits configured for connection to the plurality of cables and an electrical ground, the one or more SVL circuits having a residual voltage that is less than a minimum induced voltage generated during a power frequency fault on one or more of the plurality of conductive sheaths, but greater than a nominal operating voltage on the one or more of the plurality of conductive sheaths.

[0038] In some embodiments, the power generation system further comprises: a medium voltage transformer configured to couple the electrical power source to the plurality of cables; and generator cables that are configured to couple the medium voltage transformer to the electrical power source.

[0039] In some embodiments, the power generation system further comprises: a medium voltage-to-high voltage transformer configured to couple the plurality of cables to the transmission grid; wherein the plurality of cables are further configured to couple the medium voltage transformer to the medium voltage-to-high voltage transformer.

[0040] In some embodiments, the power generation system further comprises: utility cables that are configured to couple the medium voltage-to-high voltage transformer to the transmission grid.

Brief Description of the Drawings

[0041] The accompanying drawings, which form a part of the specification, illustrate embodiments of the present invention.

- **FIG. 1** is a schematic view of an electrical power generation system including a sheath bonding system according to some embodiments.
- **FIG. 2** is a fragmentary view of the electrical power generation system of **FIG. 1.**
- **FIG. 3** is a fragmentary view of a power transmission cable of the electrical power generation system of **FIG. 1.**
- **FIG. 4** is a schematic view of an SVL forming a part of a link box of the sheath bonding system of **FIG. 1.**
- **FIG. 5** is a top perspective view of a link box of the sheath bonding system of **FIG. 1.**
- **FIG. 6** is a fragmentary, top perspective view of the link box of **FIG. 5.**
- **FIG. 7** is a fragmentary, bottom perspective view of the link box of **FIG. 5.**
- **FIG. 8** is a top perspective view of an SVL module of the link box of **FIG. 5.**
- **FIG. 9** is an exploded, top perspective view of the SVL module of **FIG. 8.**
- **FIG. 10** is a cross-sectional view of the SVL module of **FIG. 8** taken along the line **10-10** of **FIG. 8.**
- **FIG. 11** is a cross-sectional, top perspective view of an extension housing member of the SVL module of **FIG. 8.**
- **FIG. 12** is an exploded, perspective view of a varistor stack of the SVL module of **FIG. 8.**
- **FIG. 13** is a side view of an alternative varistor stack.
- **FIG. 14** is perspective view of an insulator sleeve of the SVL module of **FIG. 8.**
- **FIG. 15** is an enlarged, fragmentary, cross-sectional view of the SVL module of **FIG. 8.**
- **FIG. 16** an exploded, top perspective view of an alternative SVL module of the link box of **FIG. 5.**
- **FIG. 17** is a cross-sectional view of the SVL module of **FIG. 16.**
- **FIG. 18** is a schematic view of an electrical power generation system including a sheath bonding system according to further embodiments.
- **FIGS. 19** and **20** illustrate the induced sheath voltages and currents, respectively, during normal operation of a cross-connected cable using a conventional SVL and an SVL according to embodiments of the inventive concept.
- **FIGS. 21** and **22** illustrate the voltage on the cross-connected cable in response to a power frequency fault using a conventional SVL and an SVL according to embodiments of the inventive concept;
- **FIGS. 23** - **26** illustrate the voltage on the cross-connected cable in response to TOV event using a conventional SVL and an SVL according to embodiments of the inventive concept.
- **FIG. 27** is a cross-section of a simulated cable configured in a single point bonding configuration;
- **FIGS. 28** - **30** illustrate the sheath induced voltages and currents of the single pointed bonded cable during steady state; and **FIGS. 31** and **32** illustrate the sheath induced voltages of a traditional SVL and **FIGS. 33** and **34** illustrate the sheath induced voltages on an SVL according to some embodiments of the inventive concept during a simulated power frequency fault.

Detailed Description of Embodiments of the Invention

[0042] The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which illustrative embodiments of the invention are shown. In the drawings, the relative sizes of regions or features may be exaggerated for clarity. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. It is noted that aspects described with respect to one embodiment may be incorporated in different embodiments although not specifically described relative thereto. That is, all embodiments and/or features of any embodiments can be combined in any way and/or combination.

[0043] It will be understood that when an element is referred to as being "coupled" or "connected" to another element, it can be directly coupled or connected to the other element or intervening elements may also be present. In contrast, when an element is referred to as being "directly coupled" or "directly connected" to another element, there are no intervening elements present. Like numbers refer to like elements throughout.

[0044] In addition, spatially relative terms, such as "under", "below", "lower", "over", "upper" and the like, may be used herein for ease of description to describe one element or feature's relationship to another element(s) or feature(s) as illustrated in the figures. It will be understood that the spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. For example, if the device in the figures is turned over, elements described as "under" or "beneath" other elements or features would then be oriented "over" the other elements or features. Thus, the exemplary term "under" can encompass both an orientation of over and under. The device may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein interpreted accordingly.

[0045] Well-known functions or constructions may not be described in detail for brevity and/or clarity.

[0046] As used herein the expression "and/or" includes any and all combinations of one or more of the associated listed items.

[0047] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0048] Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

[0049] As used herein, "monolithic" means an object that is a single, unitary piece formed or composed of a material without joints or seams. Alternatively, a unitary object can be a composition composed of multiple parts or components secured together at joints or seams.

[0050] As used herein, the term "wafer" means a substrate having a thickness which is relatively small compared to its diameter, length or width dimensions.

[0051] As used herein, "directly grounded" or "solidly grounded" means the grounded component (e.g., a cable sheath) is connected to electrical ground or earth without a permanently or conditionally electrically insulating element (e.g., a varistor) being located between the grounded component and the electrical ground.

[0052] As used herein a sheath voltage limiter (SVL) is a protective device to limit high voltage surges appearing on the open circuited sheaths of specially bonded cable system susceptible to transient voltages, which may arise, for example, from lightning, switching transients, and/or short circuit current. SVLs are configured between the sheath and ground.

[0053] As used herein, residual voltage refers to the voltage across the terminals of the SVL while it is conducting during a transient event.

[0054] As used herein, impulse current withstand capability denotes the maximum impulse current, conforming to a specified waveform, that the SVL can endure without incurring damage.

[0055] As used herein, the maximum continuous operating voltage (MCOV) U_c is the maximum voltage at which the SVL remains non-conductive and is further characterized by a leakage current that does not exceed a specified limit. An SVL configured to have an MCOV magnitude that is around 10% greater than nominal root mean square voltage of the power line.

[0056] Embodiments of the inventive concept are described herein with respect to SVLs used in conjunction with a sheaths being configured in a cross-bonding or single point bonding configuration. It will be understood that embodiments of the inventive concept are not limited to these two types of bonding configurations and other sheath bonding arrangements can be used in various embodiments of the inventive concept. With reference to **FIGS. 1, 2** and **4-7,** overvoltage protection devices (OVPD) or link boxes according to embodiments of the present invention are shown therein and designated **200-1, 200-2.** The link boxes **200-1, 200-2** may form a part of a sheath bonding or overvoltage/induced current control system **150** according to some embodiments. The sheath bonding system **150** may be incorporated into a power generation system **100** as illustrated in **FIGS. 1** and **2** in accordance with some embodiments.

[0057] The illustrated power generation system **100** includes an electrical power source **110,** generator cables **112,** a medium voltage transformer **116,** transmission cables **131, 132, 133,** a medium voltage-to-high voltage transformer **120,** utility cables **122,** an electrical power transmission grid **124,** and the sheath bonding system **150.** The generator cables **112** connect the power source **110** to the MV transformer **116,** which raises the voltage to the appropriate voltage for transmission (referred to herein as the **"medium** voltage"), as discussed in more detail below. The transmission cables **131, 132, 133** connect the MV transformer **116** to the MV/HV transformer **120.** In some embodiments, the transmission cables **131, 132,** and **133** may be arranged in a trefoil formation. Each transmission cable **131, 132, 133** conducts a respective one of the three phases of a three-phase electric power system. The MV/HV transformer **120** raises the voltage from the **medium** voltage to the appropriate voltage for transmission (referred to herein as the **"high** voltage"), as discussed in more detail below. The transmission grid **124** is connected to the HV side of the MV/HV transformer **120.**

[0058] The electrical power source **110** may be any suitable power generator(s). In some embodiments, the electrical power source **110** includes one or more wind turbine generators. In some embodiments, the electrical power source **110** includes multiple wind turbine generators each of which is connected to the MV transformer **116** (e.g., at a substation) via a respective generator cable **112.**

[0059] In some embodiments, the electrical power source **110** includes one or more photovoltaic (PV) panels. In some embodiments, the electrical power source **110** is a solar station or park including multiple PV panels or arrays of PV panels each of which is connected to the MV transformer **116** (e.g., at a substation) via a respective generator cable **112.** The system **100** may further include a DC-to-AC converter **114** between the PV panel(s) and the MV transformer **116.**

[0060] In some embodiments, the cables **131, 132, 133** are single core or conductor coaxial cables. **FIG. 3** shows the construction of the cable **131** and the cables **132, 133** may be constructed in the same manner. The cable **131** includes an electrically conductive metal main conductor **135,** an insulation layer **136** surrounding the main conductor **135,** an electrically conductive metal shield or sheath **141** surrounding the insulation **136,** and an electrically insulating jacket **137** surrounding the sheath **141.** The cable **131** may also include a semiconductor screen layer **138A** between the conductor **135** and the insulation **136** and/or a semiconductor screen layer **138B** between the insulation **136** and the sheath **141.** The sheaths of the cables **132** and **133** are designated herein as sheaths **142** and **143,** respectively.

[0061] The sheath bonding system **150** includes the link boxes **200-1, 200-2,** linking cables **152,** and cable joints **154 (FIG. 2).**

[0062] As discussed below, the sheaths **141, 142, 143** are sectionalized into sheath minor sections **141D, 141E, 141F, 142D, 142E, 142F, 143D, 143E, 143F.** The cable joints **154** electrically isolate the adjacent ends of the sheath minor sections from one another, and provide electrical connections between the linking cables **152** and the ends of the sheath minor sections. The cable joints **154** may include components to environmentally seal or protect the cable **131, 132, 133** at sheath break locations.

[0063] The link boxes **200-1** and **200-2** may be constructed in the same manner. Accordingly, it will be appreciated that the description of the link box **200-1** below likewise applies to the link box **200-2.**

[0064] The link box **200-2** includes a link box housing **202,** three SVLs **P1, P2, P3,** three metal interconnect busbars **222, 224, 226,** interconnect cables **228,** a metal ground busbar **230,** and a ground cable **232.** Each SVL **P1, P2, P3** has an SVL input terminal **218** and an SVL ground terminal **219.** The interconnect busbars **222, 224** and **226** are electrically connected to the input terminals **218** of the SVLs **P1, P2** and **P3,** respectively, by fasteners **236.**

[0065] Each SVL **P1, P2, P3** includes a varistor or varistors **215 (FIG. 4)** connected between the terminals **218, 219.** The varistor or varistors **215** are referred to hereinbelow as the varistor **215;** however, it will be appreciated that the varistor **215** may be multiple varistors electrically connected in series and/or parallel. In some embodiments, the varistors **215** are metal-oxide varistors (MOVs).

[0066] The link box **200-2** further includes a ground connector **GC** connected to the ground busbar **230** by a ground cable **232.**

[0067] The link box **200-2** further includes three input connectors **J1, J2, J3** and three output connectors **K1, K2, K3.**

[0068] The input connector **J1** and the output connector **K3** are electrically connected to one another and to the input terminal **218** of the SVL **P1** by the interconnect busbar **222.**

[0069] The input connector **J3** and the output connector **K2** are electrically connected to one another and to the input terminal **218** of the SVL **P2** by the interconnect busbar **224.**

[0070] The input connector **J2** and the output connector **K1** are electrically connected to one another and to the input terminal **218** of the SVL **P3** by the interconnect busbar **226.**

[0071] With reference to **FIGS. 1** and **2,** the cross-bonding architecture of the sheath bonding system **150** is illustrated therein. It will be appreciated that other cross-bonding architectures may be used in place of the illustrated configuration using the link boxes **200-1, 200-2.** For example, the embodiments of FIGS. 1 and 2 illustrate a cross-connection example of a cross-bonding architecture between the minor sections of sheaths of three different cables. In other embodiments, rather than cross-connecting the sheaths, the cables may be transposed in the different minor sections.

[0072] The transmission lines **131, 132, 133** each include a sheath major section **145.** In the illustrated configuration, each major section spans from the MV transformer **116** to the MV/HV transformer **120.**

[0073] Each sheath major section **145** is segmented or sectionalized into three sheath minor sections. That is, each sheath **141, 142, 143** is cut, broken or separated along the cable's axis into three sequential sheath minor sections.

[0074] The major section **145** of the sheath **141** is sectioned into sheath minor sections **141D, 141E, 141F.** The major section **145** of the sheath **142** is sectioned into sheath minor sections **142D, 142E, 142F.** The major section **145** of the sheath **141** is sectioned into sheath minor sections **143D, 143E, 143F.** Each sheath minor sections **141D, 141E, 141F, 142D, 142E, 142F 143D, 143E, 143F** has opposed ends **147** and **148 (FIG. 2).**

[0075] The ends of each major section **145** are solidly connected to electrical ground. For example, each end of a major section 145 may be connected to ground at a transformers **116, 120** or the beginning of another major section.

[0076] The ground busbars **230** of the link boxes **200-1, 200-2** are connected to electrical ground at their ground connectors **GC.**

[0077] The minor sheath section ends **147, 148** that are not at the end of a major section **145** are connected to the input connectors **J1, J2, J3** and output connectors **K1, K2, K3** of the link boxes **200-1, 200-2** as schematically illustrated in **FIG. 2.** The minor sheath sections **141D, 141E, 141F, 142D, 142E, 142F, 143D, 143E, 143F** of the three sheaths **141, 142, 143** are thereby electrically cross-connected in and by the link boxes **200-1, 200-2** as schematically illustrated in **FIG. 2.**

[0078] Additionally, by the link box **200-1** the minor sheath sections **141D, 143E** are connected to ground through the SVL **P1,** the minor sheath sections **143D, 142E** are connected to ground through the SVL **P2,** and the minor sheath sections **142D, 141E** are connected to ground through the SVL **P3.** In the link box **200-1,** the minor sheath sections **141E, 143F** are connected to ground through the SVL **P1,** the minor sheath sections **143E, 142F** are connected to ground through the SVL **P2,** and the minor sheath sections **142E, 141F** are connected to ground through the SVL **P3.** These minor sheath sections are connected to ground only indirectly or selectively, as discussed herein. That is, the SVLs **P1, P2, P3** do not directly bond the sheaths **141, 142, 143** to ground.

[0079] The SVLs **P1, P2, P3** electrically isolate the ends of the minor sheath sections from ground except in response to conditions that cause SVLs to conduct. More particularly, the varistor **215** of each SVL **P1, P2, P3** electrically insulates the sheaths from ground or electrically connects the sheaths to ground, depending on the conditions of the system and the state of the varistor **215.** Additionally, each SVL **P1, P2, P3** has a fail-safe system **217** that causes the SVL **P1, P2, P3** to short or connect the associated sheaths to ground in response to some conditions or events. Each fail-safe system **217** may include multiple fail-safe mechanisms that respond to different conditions or events.

[0080] As is well known, a varistor has an innate nominal clamping voltage VNOM (sometimes referred to as the "breakdown voltage" or simply the "varistor voltage") at which the varistor begins to conduct current. Below the VNOM, the varistor will not pass current. Above the VNOM, the varistor will conduct a current (*i.e.,* a leakage current or a surge current). The VNOM of a varistor is typically specified as the measured voltage across the varistor with a DC current of 1mA.

[0081] As is known, a varistor has three modes of operation. In a first normal mode (discussed above), up to a nominal voltage, the varistor is practically an electrical insulator. In a second normal mode (also discussed above), when the varistor is subjected to an overvoltage, the varistor temporarily and reversibly becomes an electrical conductor during the overvoltage condition and returns to the first mode thereafter. In a third mode (the so-called end of life mode), the varistor is effectively depleted and becomes a permanent, non-reversible electrical conductor.

[0082] The varistor also has an innate clamping voltage VC (sometimes referred to as simply the "clamping voltage"). The clamping voltage VC is defined as the maximum voltage measured across the varistor when a specified current is applied to the varistor over time according to a standard protocol. The clamping voltage may also be referred to as the residual voltage.

[0083] In the absence of an overvoltage condition, the varistor **215** provides high resistance such that no current flows through the SVL **P1, P2, P3** as it appears electrically as an open circuit. That is, ordinarily the varistor **215** passes no current. The terminals **218, 219** are electrically isolated from one another by the varistor **215.** In the event of an overcurrent surge event (typically transient; *e.g.*, lightning strike) or an overvoltage condition or event (typically longer in duration than an overcurrent surge event) exceeding VNOM, the resistance of the varistor wafer decreases rapidly, allowing current to flow through the SVL **P1, P2, P3** and create a shunt path for current flow to ground. Normally, the varistors **150** recover from these events without significant overheating of the SVL **P1, P2, P3.**

[0084] The VNOM of a given varistor begins at a certain value and over time could degrade to a lower effective VNOM value as a result of varistor aging. Typically, a varistor is initially rated for a "maximum continuous operating voltage" (MCOV), indicating that the VNOM of the varistor exceeds the rated MCOV when first placed in service. Typically, the maximum continuous operating voltage, which may be denoted as U_c, is around 10% higher than the nominal root mean square voltage between the conductor and earth ground.

[0085] Varistor aging (*i.e,* degradation resulting in reduction of the VNOM) can be caused by surge currents or continuous leakage currents (during continuous overvoltage events) applied to the varistor in service, as well as by passage of time with the nominal voltage applied on the varistor (rare case, typically caused by low quality varistors). Aging degradation is generally thermally induced.

[0086] Varistors have multiple failure modes. The failure modes include: 1) the varistor fails as a short circuit; and 2) the varistor fails as a linear resistance. The failure of the varistor to a short circuit or to a linear resistance may be caused by the conduction of a single or multiple surge currents of sufficient magnitude and duration or by a single or multiple continuous overvoltage events that will drive a sufficient current through the varistor.

[0087] A short circuit failure typically manifests as a localized pinhole or puncture site (herein, "the failure site") extending through the thickness of the varistor. This failure site creates a path for current flow between the two electrodes of a low resistance, but high enough to generate ohmic losses and cause overheating of the device even at low fault currents. Sufficiently large fault current through the varistor can melt the varistor in the region of the failure site and generate an electric arc.

[0088] A varistor failure as a linear resistance will cause the conduction of a limited current through the varistor that will result in a buildup of heat. This heat buildup may result in catastrophic thermal runaway and the device temperature may exceed a prescribed maximum temperature. For example, the maximum allowable temperature for the exterior surfaces of the device may be set by code or standard to prevent combustion of adjacent components. If the leakage current is not interrupted at a certain period of time, the overheating will result eventually in the failure of the varistor to a short circuit as defined above.

[0089] In some cases, the current through the failed varistor could also be limited by the power system itself (*e.g.,* ground resistance in the system or in photo-voltaic (PV) power source applications where the fault current depends on the power generation capability of the system at the time of the failure) resulting in a progressive build up of temperature, even if the varistor failure is a short circuit. There are cases where there is a limited leakage current flow through the varistor due to extended in time overvoltage conditions due to power system failures, for example. These conditions may lead to temperature build up in the device, such as when the varistor has failed as a linear resistance and could possibly lead to the failure of the varistor either as a linear resistance or as a short circuit as described above.

[0090] In some cases, the varistor **215** may assume an "end of life" mode in which the varistor **215** is depleted in full or in part (*i.e,* in an "end of life" state), leading to an end of life failure. When the varistor **215** reaches its end of life, the varistor **215** will become substantially a short circuit with a very low but non-zero ohmic resistance.

[0091] As a result, in an end of life condition, a fault current will continuously flow through the varistor **215** even in the absence of an overvoltage condition. In this case, the current may continue to flow through the varistor **215,** thereby generating heat from ohmic losses in the varistor **215.** If the condition was permitted to persist, the heat generated in the SVL **P1, P2, P3** could build up until the SVL **P1, P2, P3** melts or explodes. Such an event may be regarded as catastrophic. If the fault current were of sufficient magnitude, the fault current may induce or generate electric arcing through and around the varistor **215** (herein, an "arcing event"). Such an arcing event may rapidly generate additional heat in the SVL **P1, P2, P3** and/or may cause localized damage to other components of the link box **200-1, 200-2.**

[0092] In the case of the SVLs **P1, P2, P3,** the fail-safe system **217** of each SVL **P1, P2, P3** is adapted and configured to electrically short circuit the current applied to the SVL **P1, P2, P3** around the varistor **215** to prevent or reduce the generation of heat in the varistor. In this way, the fail-safe system **217** can operate as a switch to bypass the varistor **215** and prevent overheating and catastrophic failure as described above.

[0093] According to embodiments of the invention, the fail-safe system **217** includes two fail-safe mechanisms that operate independently of one another. More particularly, in some embodiments, the first fail-safe mechanism will operate to short circuit the SVL **P1, P2, P3** when a first type or set of operating conditions are experienced by the SVL **P1, P2, P3** and the second fail-safe mechanism will operate to short circuit the SVL **P1, P2, P3** when a second type or set of operating conditions, different from the first, are experienced by the SVL **P1, P2, P3.** That is, under different circumstances, the first fail-safe mechanism may operate or execute first or the second fail-safe mechanism may operate or execute first. Ordinarily, though not necessarily, only one of the fail-safe mechanisms will execute, whereupon the conditions necessary to invoke the other fail-safe mechanism will be prevented from arising.

[0094] The power generation system **100,** the sheath cross-bonding system **150,** and the SVLs **P1, P2, P3** will operate as follows in use. Referring now to **FIGS.** 1 and **2,** during normal operation, as the current from the source **110** is transmitted through the main conductors **135** of the phase cables **131, 132, 133** to the transformer **116,** voltages will be developed on the conductors **135,** which may capacitively induce voltages on the sheaths **141, 142,** and **143** surrounding the conductors.

[0095] The cross-bonding of the sheath minor sections **141D, 141E, 141F, 142D, 142E, 142F, 143D, 143E, 143F** serves to reduce or eliminate circulating currents induced in the sheaths **141, 142, 143** by the current transmitted through the main conductors **135** of the cables **131, 132, 133.** The mechanism by which this occurs is well-known to those of skill in the art and will not be described in detail herein. Generally, the inner ends of the outer minor sections **141D, 142D, 143D, 141F, 142F, 143F** and both ends of the middle minor sections **141E, 142E, 143E** are cross-connected by the link boxes **200-1, 200-2.** The phase voltages on the sheaths **141, 142, 143** are 120 degrees apart and substantially equal. The sheath minor sections **141D, 141E, 141F, 142D, 142E, 142F, 143D, 143E, 143F** are cross-connected such that the net induced voltage on each major section **145** is near-zero. That is, the sheath voltages cancel one another or sum up to a small value and the sheath induced currents sum up to near zero. The ends of the sheath minor sections are electrically isolated from one another except via the link box connections. In some cases, the sections of the cables corresponding to the sheath minor sections are physically transposed to reduce any residual sheath voltage.

[0096] SVLs may be placed in a link box to prevent or reduce damage to a cable sheath during TOV events, such as lightning strikes. If lightning strikes the earth near the grounding point of the sheath or the grounding point itself, the sheath can conduct the lightning, which may create a traveling wave that reflects at junctions where the resistance changes, such as the line termination or the cable joints. This can create standing waves throughout the cable line, which may cause overvoltages that can damage the cable jacket. The overvoltage created by the lightning strike can be significant and may damage the cable jacket at multiple points.

[0097] Conventionally, an SVL may be configured with both a conducting characteristic, i.e., residual voltage, that is greater than a worse case induced power frequency voltage, but is less than an induced voltage resulting from a TOV event, such as a lightning strike. Typically, each SVL would also be configured with an MCOV characteristic that is greater the worse case inducted power frequency voltage to ensure that the SVL does not conduct during power frequency faults, such as short circuits. These SVLs may, however, provide paths to ground for traveling waves generated in the cable sheaths due to TOV events, such as lightning strikes. The SVLs may further limit the overvoltage of the traveling wave to the residual voltage of the SVLs in the link box. Preventing or reducing these overvoltages may reduce the severity of any damage to the cable jacket thereby reducing the likelihood of costly repairs. SVLs configured with these residual voltage and MCOV characteristics and used on medium voltage cables **131, 132, 133** would not, however, protect the sheaths **141, 142, 143** from damage resulting from power frequency faults. According to some embodiments of the inventive concept, each link box **200-1** and **200-2** includes one or more SVLs **P1, P2,** and **P3** that are configured to have a residual voltage and MCOV that are each less than a minimum induced voltage generated on a sheath during a power frequency fault, but greater than the nominal operating voltage on the medium voltage cable sheath. The residual voltage, in some embodiments may be about 80% to about 90% of the minimum induced voltage generated during a power frequency fault. In some embodiments, the minimum induced voltage generated during a power frequency fault may be about 500 volts - 1000 volts. During a transient power frequency fault event, the voltage induced into the sheaths **141, 142,** and **143** exceeds the effective residual or clamping voltage of the SVLs **P1, P2,** and **P3,** which causes the SVLs **P1, P2,** and **P3** to enter a conductive state to divert current to ground as shown in **FIGS. 1** and **2.**

[0098] Thus, according to some embodiments of the inventive concept, the SVLs **P1, P2,** and **P3** used in the link boxes **200-1** and **200-2** are configured with residual voltage and MCOV characteristics that allow the SVLs to conduct and thereby divert current to ground in response to both TOV events, such as lightning strikes, as well power frequency faults, such as short circuits.

[0099] Embodiments of the inventive concept may be illustrated by way of example. A power line is simulated with three conductive cables configured in a cross-connect configuration of a cross-bonding architecture with an 18 km main section divided into three 6 km minor sections. The simulation was performed using SVLs that are configured to conduct only in response to TOV events, such as lightning strikes, but not conduct in response to power frequency faults and using SVLs that are configured to conduct in response to TOV events and power frequency faults. **FIGS. 19** and **20** illustrate the induced sheath voltages and currents, respectively during normal operation, i.e., no TOV event or power frequency fault event. **FIGS. 21** and **22** illustrate the voltage on the cable in response to a power frequency fault, which is simulated as a 1.5kA short circuit. **FIG. 21** is a graph of the voltage on the cable in which the SVLs are configured to conduct only in response to TOV events and **FIG. 22** is graph of the voltage on the cable in which the SVLs are configured to conduct in response to TOV events and power frequency faults.

	Maximum Induced Sheath Voltage [V]
SVL for TOV event only	2315
SVL for TOV event and power frequency fault	2117

As shown in the graphs and highlighted in the table, the maximum induced voltage in all phases was reduced by ~10% ($200V_{rms}$) when using the SVLs configured for both TOV events and power frequency faults. The SVLs configured to conduct during power frequency faults will start conducting to prevent high induced voltages on the sheath without compromising the low residual voltage during lightning events. FIGS. 23 - 26 illustrate the voltage on the cable in response to TOV event, such as a lightning strike. During a lightning event the two SVL configurations have a large difference in their residual voltage. To see the difference of the traditional SVL (U_c=2800V) and the SVL configured to conduct in response to both TOV events and power frequency faults two simulations were performed. Both SVL types were tested with an 8/20μs impulse current (8μs front time and 20μs time to half). Two different impulses were tested. One at 10kA per SVL (FIGS. 23 and 24) and one at 40kA (FIGS. 25 and 26). The simulation results are depicted below. The residual voltages of all the simulations are tabulated below:

	Impulse Current [kA]	Residual Voltage [kV]
SVL for TOV event only	10.0	11.34
	40.5	12.57
SVL for TOV event and power frequency fault	10.1	1.13
	40.3	1.25

Due to the lower residual voltage, the SVL configured for both TOV events and power frequency faults protects the cable jacket from overvoltages due to lightning events better than the traditional SVLs that are designed to not conduct during power frequency faults. The main reason for that difference in their residual voltage is the difference in the handling of power frequency faults. The traditional SVL has a higher U_c (and so, a higher residual voltage) as it is designed to not conduct during a short - circuit event, in juxtaposition to the SVL configured to conduct during power frequency faults, which has a lower U_c (and by extension a lower residual voltage), which is designed to conduct during a short - circuit event and lower the induced sheath voltage.

[0100] With reference to **FIGS. 8-15,** an SVL module **300** according to some embodiments is shown therein. According to some embodiments, each of the SVLs **P1, P2, P3** as discussed herein is constructed and operate as disclosed for the SVL module **300.**

[0101] With reference to **FIGS. 9** and **10,** the SVL module **300** includes a housing assembly **311,** a varistor stack **351,** an electrical insulator stack assembly **360,** an electrical insulator membrane **370,** an insulation cover **376,** an insulation cap **378,** a first fail-safe mechanism **306** (which uses arc fusing), and a second fail-safe mechanism **308** (including a meltable member **372).**

[0102] The module housing assembly **311** includes and is collectively formed by a lower housing assembly or housing electrode **310,** an inner electrode **340,** an end cap **312,** fasteners **314,** and a compression member **348.** The housing electrode **310** serves as a second electrode opposite the inner electrode **340.** The housing electrode **310** serves an outer electrode.

[0103] The lower housing assembly or housing electrode **310** includes two discreet housing parts (namely, a first housing part or member or base housing member **320** and a second housing part or member or extension housing member **330)** and an annular sealing member **316.** The housing electrode **310** includes a tubular housing side wall **317** and defines a housing cavity **319.**

[0104] The base housing member **320** is a cup-shaped metallic structure. The base housing member **320** has an end or electrode wall **322** and an integral tubular, cylindrical side wall **323** extending from the end wall **322.** The inner surface of the side wall **323** is cylindrical. The side wall **323** and the end wall **322** form a chamber or base cavity **325** communicating with an opening. A threaded terminal post **324** (which serves as the SVL terminal **219)** projects axially outwardly from the end wall **322.** The end wall **322** has an inwardly facing, substantially planar contact surface **322A.** A male screw thread **326** is formed on the outer surface of the side wall **323** at the opening. An annular, substantially planar contact surface **323A** is provided below the thread **326** proximate the upper end of the side wall **323.** An O-ring groove **328** and a cover locator feature or groove are also defined in the outer surface of the side wall **323.**

[0105] According to some embodiments, the base housing member **320** is formed of metal. According to some embodiments, the base housing member **320** is formed of aluminum. According to some embodiments, the base housing member **320** is unitary and, in some embodiments, monolithic. The base housing member **320** as illustrated is cylindrically shaped, but may be shaped differently.

[0106] The extension housing member **330 (FIG. 11)** includes a cylindrical, tubular side wall **333** defining a passage **335** and opposed end openings. A female screw thread **336** is formed on the outer surface of the side wall **333** at the lower opening. An annular, substantially planar contact surface **333A** is provided below the thread **336** at the lower end of the side wall **333.** A locking groove **339** is also defined in the outer surface of the side wall **333.** Fastener holes **338** (*e.g.,* three or more) are defined in the upper end of the side wall **333.**

[0107] The extension housing member **330** includes an annular, integral flange **334** that projects radially inward from the inner surface of the side wall **333.** The flange **334** includes an annular, planar top face **334A,** an annular, planar bottom face **334C,** and an annular, inwardly facing, rounded side face **334B.**

[0108] According to some embodiments, the extension housing member **330** is formed of metal. According to some embodiments, the extension housing member **330** is formed of aluminum. According to some embodiments, the extension housing member **330** is unitary and, in some embodiments, monolithic. The extension housing member **330** as illustrated is cylindrically shaped, but may be shaped differently.

[0109] According to some embodiments, the annular sealing member **316** is an O-ring. The sealing member **316** may be of any suitable material. According to some embodiments, the sealing member **316** is formed of a resilient material, such as an elastomer.

[0110] With reference to **FIG. 10,** the O-ring **316** (or other sealing member) is seated in the groove **328.** The base housing member **320** and the extension housing member **330** are securely fixed together or joined by mating and screwing together the threads **326** and **336** to form a joint **HJ.** The members **320, 330** are sealed at the joint **HJ** by the O-ring. The members **320, 330** together form a strong, rigid cup-shaped structure. The members **320, 330** are electrically connected by contact mating between the contact surfaces **323A, 333A.** The base housing member **320** and the extension housing member **330** are thus axially stacked along the module axis **A-A** and in electrical continuity with one another. The base housing member tubular side wall **323** and the extension housing member tubular side wall **333** each form a portion of the housing side wall **317.** The base housing member cavity **325** and the extension housing member passage **335** form respective portions of the housing cavity **319.**

[0111] The SVL housing assembly **311** defines an environmentally sealed, enclosed module chamber **304** that includes the cavity **325** and the passage **335.** The module chamber **304** is partitioned into an upper or meltable member chamber **304U** and a lower or varistor chamber **304L,** by the flange **334** and the inner electrode **340.**

[0112] The inner electrode **340** has a head **344** disposed in the module chamber **304** and an integral shaft **342** (corresponding to the terminal **218** of the SVLs **P1, P2, P3)** that projects outwardly through the upper opening of the housing **310.**

[0113] The head **344** has a substantially planar contact surface **344A** that faces the contact surface **322A** of the electrode wall **322.** The head **344** also has an annular outer side surface **344B.**

[0114] An integral, annular flange **346** extends radially outwardly from the shaft **342.** An annular, sidewardly opening groove **345** is defined by the flange **346** and the head **344** therebetween. A threaded terminal bore **342A** is formed in the end of the shaft **342** to receive a bolt for securing the electrode **340** to a cable or busbar, for example.

[0115] According to some embodiments, the inner electrode **340** is formed of aluminum. However, any suitable electrically conductive metal may be used. According to some embodiments, the inner electrode **340** is unitary and, in some embodiments, monolithic.

[0116] The end cap **312** is substantially plate-shaped and has a profile matching that of the top end of the extension housing member **330.** A shaft opening and screw holes are defined in the end cap **312.**

[0117] According to some embodiments, the end cap **312** is formed of an electrically conductive material. In some embodiments, the end cap **312** is formed of a metal and, in some embodiments, it is formed of aluminum.

[0118] The meltable member **372** is annular and is mounted on the inner electrode **340** in the groove **345** within the upper chamber **304U.** In some embodiments and as shown, the meltable member **372** is a cylindrical, tubular piece or sleeve. According to some embodiments, the meltable member **372** contacts the shaft **342** and, according to some embodiments, the meltable member **372** contacts the shaft **342** along substantially the full length of the meltable member **372** and the full length of the shaft **342.** The meltable member **372** may also engage the lower surface of the flange **334** and the top surface of the head **344.** The meltable member **372** is spaced apart from the side wall **333** a distance sufficient to electrically isolate the meltable member **372** from the side wall **333.**

[0119] The meltable member **372** is formed of a heat-meltable, electrically conductive material. According to some embodiments, the meltable member **372** is formed of metal. According to some embodiments, the meltable member **372** is formed of an electrically conductive metal alloy. According to some embodiments, the meltable member **372** is formed of a metal alloy from the group consisting of aluminum alloy, zinc alloy, and/or tin alloy. However, any suitable electrically conductive metal may be used.

[0120] According to some embodiments, the meltable member **372** is selected such that its melting point is greater than a prescribed maximum standard operating temperature. The maximum standard operating temperature may be the greatest temperature expected in the meltable member **372** during normal operation (including handling overvoltage surges within the designed for range of the OVPD module **300)** but not during operation which, if left unchecked, would result in thermal runaway. According to some embodiments, the meltable member **372** is formed of a material having a melting point in the range of from about 80 to 160 °C and, according to some embodiments, in the range of from about 80 to 120 °C. According to some embodiments, the melting point of the meltable member **372** is at least 20 °C less than the melting points of the extension housing member **330,** the inner electrode **340** and the membrane **370,** and, according to some embodiments, at least 40 °C less than the melting points of those components.

[0121] According to some embodiments, the meltable member **372** has an electrical conductivity in the range of from about 0.5×10^6 Siemens/meter (S/m) to 4×10^7 S/m and, according to some embodiments, in the range of from about 1×10^6 S/m to 3×10^6 S/m.

[0122] The meltable member **372** can be mounted on the electrode **340** in any suitable manner. According to some embodiments, the meltable member **372** is cast or molded onto the electrode **340.** According to some embodiments, the meltable member **372** is mechanically secured onto the electrode **340.** According to some embodiments, the meltable member **372** is unitary and, in some embodiments, monolithic.

[0123] A first annular gap **G1 (FIG. 15)** is defined radially between the head **344** and the flange side face **334B.** According to some embodiments, the gap **G1** has a radial width **W1** in the range of from about 0.1 mm to 1.0 mm.

[0124] A second annular gap **G2 (FIG. 10)** is defined radially between the meltable member **372** and the side wall **333.**

The gap **G2** defines a tubular void that circumferentially surrounds the meltable member **372.** The gap **G2** has a larger radial width than the width of the gap **G1**.

[0125] The varistor stack **351 (FIGS. 9** and **12)** includes a plurality of varistor members **350** and a plurality of internal parallelization or interconnect members **354.** The varistor members **350** and the interconnect members **354** are axially stacked in the lower chamber **304L** between the electrode head **344** and the electrode end wall **322** and form the varistor stack **351.** The varistor members **350** and the interconnect members **354** are axially aligned along a varistor stack axis **V-V,** which may be parallel or coaxial with the SVL module axis **A-A.** The interconnect members **354** electrically interconnect the varistor members **350** and the electrodes **310, 340.**

[0126] The arrangement of the varistor members **350** and the interconnect members **354** may electrically connect the varistor members **350** in electrical parallel between the electrodes **310, 340,** in electrical series between the electrodes **310, 340,** or in both electrical parallel and electrical series between the electrodes **310, 340.** In the embodiment illustrated in **FIG. 9,** the varistor stack **351** includes three varistor members **350** and two interconnect members **354** arranged to provide three varistors **350** in parallel. However, other numbers and arrangements of the varistor members **350** and interconnect members **354** may be provided.

[0127] In alternative embodiments, the varistor stack can include multiple substacks of varistors stacked in electrical series, with each substack including a plurality of parallel-connected varistors. For example, in the embodiment illustrated in **FIG. 13,** an alternative varistor stack **351'** includes fifteen varistor members **350'** and twelve interconnect members **354'** arranged to provide three varistor substacks **353'** in series, with each varistor substack **353'** including five varistors **350'** in parallel.

[0128] In alternative embodiments, some or all of the varistor members **350** are stacked without interconnect members **354.** For example, the SVL module may be assembled with no interconnect members **354.**

[0129] According to some embodiments, each varistor member **350** is a varistor wafer (*i.e.*, is wafer- or disk-shaped). In some embodiments, each varistor wafer **350** is circular in shape and has a substantially uniform thickness. However, varistor wafers **350** may be formed in other shapes. The thickness and the diameter of the varistor wafers **350** will depend on the varistor characteristics desired for the particular application.

[0130] Each varistor wafer **350** has first and second opposed, substantially planar contact surfaces **352.**

[0131] The varistor material may be any suitable material conventionally used for varistors, namely, a material exhibiting a nonlinear resistance characteristic with applied voltage. Preferably, the resistance becomes very low when a prescribed voltage is exceeded. The varistor material may be a doped metal oxide or silicon carbide, for example. Suitable metal oxides include zinc oxide compounds.

[0132] Each varistor wafer **350** may include a wafer of varistor material coated on either side with a conductive coating so that the exposed surfaces of the coatings serve as the contact surfaces **352.** The coatings can be metallization formed of aluminum, copper or silver, for example. Alternatively, the bare surfaces of the varistor material may serve as the contact surfaces **352.**

[0133] The interconnect members **354** are electrically conductive. Each interconnect member **354** includes a pair of axially spaced apart, disk-shaped contact portions **355** joined by a bridge portion **356.**

[0134] According to some embodiments, each contact portion **355** is substantially planar, relatively thin and wafer- or disk-shaped. In some embodiments, each contact portion **355** has a diameter to thickness ratio of at least 10. In some embodiments, the thickness of each contact portion **355** is in the range of from about 0.4 mm to 3.0 mm.

[0135] According to some embodiments, each contact portion **355** does not have any through holes extending through the thickness of the contact portion.

[0136] According to some embodiments, the interconnect members **354** are formed of copper. However, any suitable electrically conductive metal may be used. According to some embodiments, the interconnect members **354** are unitary and, in some embodiments, monolithic.

[0137] In the varistor stack **351,** the contact portions **355** of the interconnect members **354** are interposed or sandwiched between the varistor wafers **350.** The contact portions **355** engage respective ones of the varistor wafer contact surfaces **352.** Each said engagement forms an intimate physical or mechanical contact between the interconnect member contact portions and varistor contact surfaces. Each said engagement forms a direct electrical connection or coupling between the interconnect member contact portions and varistor contact surfaces.

[0138] The endmost electrical contact surfaces **351U** and **351L** form the effective electrical contacts between the varistor assembly stack **351** and the electrodes **344** and **310,** respectively. The endmost electrical contact surfaces **351U** and **351L** may each be a varistor contact face **352,** a contact portion **355,** or an additional electrically conductive component (*e.g.,* a metal spacer plate).

[0139] The insulator stack assembly **360 (FIG. 10)** includes an insulator body or sleeve **362** and a pair of gaskets **368.** The insulator sleeve **362** and the gaskets **368** are axially stacked in the lower chamber **304L** between the flange **334** and the electrode wall **322.** In other embodiments, the insulator stack assembly includes multiple stacked sleeves **362** with additional gaskets **368** separating adjacent sleeves **362.**

[0140] The insulator sleeve **362 (FIG. 14)** is tubular and includes a side wall **366A** defining a through passage **366B.** The outer surface of the insulator sleeve **362** is cylindrical and sized and shaped to substantially match the contour of the inner surface of the side wall **323.** The inner surface of the insulator sleeve **362** is partially cylindrical to match the contours of the varistor wafers **350.** Axially extending slots or receiver channels **366D** are defined in the inner surface of the side wall **366A.** The insulator sleeve **362** has axially opposed end faces **366E.**

[0141] The top end of the insulator sleeve **362** further includes an annular barrier flange **366F** on its upper end. The barrier flange **366F** extends radially inward.

[0142] The insulator sleeve **362** is formed of an electrically insulating material. According to some embodiments, the insulator sleeve **362** is formed of an electrically insulating ceramic. Suitable ceramic insulation materials may include alumina, zirconia, zirconia toughened alumina (ZTA), or silicon nitride. According to some embodiments, the insulator sleeve **362** is formed of an electrically insulating high temperature plastic. Suitable high temperature insulation materials may include ULTEM™ 1000, KETRON® 1000 PEEK and similar materials.

[0143] The gaskets **368** are annular and may be flat. Some or all the gaskets **368** may include side notches, cut outs or recesses **368A.** The gaskets **368** may be shaped the same as or similar to the shapes of the engaging end faces **366E** of the insulator sleeve **362.**

[0144] In some embodiments, the gaskets **368** may be formed of an electrically insulating, resilient, elastomeric material. According to some embodiments, the gaskets **368** are formed of rubber. According to some embodiments, the gaskets **368** are formed of silicone rubber. Suitable materials may include silicone rubber (*e.g.*, VMQ silicone rubber), Styrene Butadiene rubber (SBR), or Polyurethane (PU) elastomers.

[0145] In some embodiments, each gasket **368** has a thickness in the range of from about 1 mm to 3 mm.

[0146] The gaskets **368** are axially interposed between the end faces **366E** of the insulator sleeve **362** and the mating faces **322A, 334C** of the housing **310.** The recesses **368A** are aligned with the receiver channels **366D.** The insulator stack assembly **360** circumferentially surrounds the varistor stack **351** through the chamber **304L.** The varistor stack **351** is thus separated from the side wall **323** by the insulator stack assembly **360** which is radially interposed therebetween. The barrier flange **366F** is positioned immediately below the flange **334** and surrounds the bottom of the head **344.**

[0147] The membrane **370 (FIGS. 9** and **15)** is tubular, relatively thin, and generally cylindrical. The membrane **370** circumferentially surrounds the head **344.** In some embodiments, the membrane **370** substantially fully fills the gap **G1**. In some embodiments, the membrane **370** extends from a top edge above the flange **334** (*i.e,* in the upper chamber **304U)** to a bottom edge below the flange **334.** In some embodiments, the bottom edge coincides with the bottom end of the head **344.** In some embodiments, the membrane **370** circumferentially surrounds a lower portion of the meltable member **372.**

[0148] The membrane **370** is formed of a dielectric or electrically insulating material having high melting and combustion temperatures, but which can be disintegrated (such as by melting, burning, combusting or vaporizing) when subjected to an electric arc or the high temperatures created by an electric arc.

[0149] According to some embodiments, the membrane **370** is formed of a high temperature polymer and, in some embodiments, a high temperature thermoplastic. In some embodiments, the membrane **370** is formed of polyetherimide (PEI), such as ULTEM™ thermoplastic available from SABIC of Saudi Arabia. In some embodiments, the membrane **370** is formed of non-reinforced polyetherimide or polypropylene.

[0150] According to some embodiments, the membrane **370** is formed of a material having a melting point greater than the melting point of the meltable member **372.** According to some embodiments, the membrane **370** is formed of a material having a melting point in the range of from about 120 to 200 °C and, according to some embodiments, in the range of from about 140 to 160° C.

[0151] According to some embodiments, the membrane **370** material can withstand a voltage of 25 kV per mm of thickness.

[0152] According to some embodiments, the membrane **370** has a nominal thickness **T2 (FIG. 15)** in the range of from about 0.1 to 0.5 mm and, in some embodiments, of 0.3 to 0.4 mm.

[0153] The compression member **348** is annular and includes a shaft opening **348A.** The compression member **348** includes an annular main body **348B,** an integral, annular upper flange **348C** and an integral, annular lower flange **348D.**

[0154] The compression member **348** is formed of an electrically insulating, resilient, elastomeric material. According to some embodiments, the compression member **348** is formed of a material having a hardness in the range of from about 60 Shore A to 85 Shore A. According to some embodiments, the compression member **348** is formed of rubber. According to some embodiments, the compression member **348** is formed of silicone rubber.

[0155] The main body **348B** of the compression member **348** is captured axially between the end cap **312** and the electrode upper flange **346.** The upper flange **348C** extends through the end cap opening **312A** and the shaft **342** of the electrode **340** extends through the opening **348A,** so that the upper flange **348C** fills the circumferential gap between the shaft **342** and the end cap **312.** The lower flange **348D** surrounds the electrode flange **346** so that the lower flange **348D** fills the circumferential gap between the electrode flange **346** and the side wall **323.**

[0156] The compression member **348** serves to electrically insulate the housing electrode **310** from the inner electrode **340.** The compressed compression member **348** can also form a seal to constrain or prevent overvoltage event byproducts, such as hot gases and fragments from the varistor wafers **350** from escaping the enclosed chamber **304**

through the housing electrode opening **335A.**

[0157] The main body **348B** of the compression member **348** is captured between the end cap **312** and the electrode upper flange **346** and axially compressed (*i.e,* axially loaded and elastically deformed from its relaxed state) so that the compression member **348** serves as a biasing member and applies a persistent axial pressure or load to the inner electrode **340** and the end cap **312.** The compression member **348** thereby persistently biases, presses or loads the electrode head **344** and the end wall **322** against the varistor stack **351** along a load or clamping axis in convergent directions to ensure firm and uniform engagement between the interfacing contact surfaces of the head **344,** the end wall **322,** the varistor members **336,** and the interconnect members **354.** In some embodiments, the clamping axis is substantially coincident with the axis **A-A.**

[0158] The cover **376** is used to provide electrical insulation between the housing assembly **311** and surrounding space. The cover **376** is tubular and includes integral upper and lower lock flanges **376A.** The cover **376** is configured to fit snugly around the housing electrode **310,** extend from end to end. The cover upper and lower lock flanges **376A** lock the cover **376** on the housing assembly **311.**

[0159] The insulation cover **376** may be formed of any suitable electrically insulating material. According to some embodiments, the cover **376** is formed of rubber. According to some embodiments, the cover **376** is formed of silicone rubber.

[0160] The insulation cap **378** provides electrical insulation between the inner electrode **340,** the end cap **312,** the housing electrode **310** and surrounding space. The insulation cap **378** is generally cup-shaped. The cap **378** includes an opening that snugly receives the compression member upper flange **348C.** The cap **378** includes an annular flange **378B** that is snugly interposed between the insulation cover **376** and the housing member **330.** The flange **378B** is provided with one or more latch features that interlock with the locking groove **339** of the extension housing member **330** to secure the cap **378.**

[0161] The insulation cap **378** may be formed of any suitable electrically insulating material. According to some embodiments, the insulation cap **378** is formed of rubber. According to some embodiments, the insulation cap **378** is formed of silicone rubber.

[0162] The SVL module **300** is assembled as shown in **FIG. 10.** When assembled, the flange **334** presses against the insulator stack **360** to fix the insulator stack **360** in place. In some embodiments, the components are configured such that the gaskets **368** are resiliently or elastically deformed and tend to push the insulator sleeves **362, 364** apart. The end cap **312** is bolted to the upper end of the extension housing member **330** using fasteners **314** and holes **338,** thereby compressing the compression member **348,** which in turn presses the inner electrode **340** against the varistor stack **351.**

[0163] As discussed above, an SVL module as described can used for each of the SVLs **P1, P2, P3.** The terminal **342** corresponds to the input terminal **218.** The terminal **324** corresponds to the output terminal **219.** The fail-safe mechanisms **306, 308** correspond to the fail-safe system **217.**

[0164] The head **344,** flange **334,** varistor stack **351,** and membrane **370** are relatively constructed and configured to form the first fail-safe system **306.** The meltable member **372** and the electrodes **340, 310** are relatively constructed and configured to form the second fail-safe system **308.** The first fail-safe system **306** and the second fail-safe system **308** provide safe failure modes for the SVL module **300.** The fail-safe systems **306, 308** are adapted to prevent or inhibit overheating or thermal runaway of the SVL module **300,** as discussed in more detail below.

[0165] The first fail-safe system **306** and the second fail-safe system **308** are each adapted and configured to electrically short circuit the current applied to the SVL module **300** around the varistor **350** to prevent or reduce the generation of heat in the varistor. In this way, the fail-safe systems **306, 308** can operate as switches to bypass the varistor **350** and prevent overheating and catastrophic failure as described above. According to embodiments of the invention, the fail-safe systems **306, 308** operate independently of one another. More particularly, in some embodiments, the fail-safe system **306** will operate to short circuit the SVL module **300** when a first type or set of operating conditions are experienced by the SVL module **300** and the fail-safe system **308** will operate to short circuit the SVL module **300** when a second type or set of operating conditions, different from the first, are experienced by the SVL module **300.** That is, under different circumstances, the fail-safe system **308** may operate or execute first or the fail-safe system **306** may operate or execute first. Ordinarily, though not necessarily, only one of the fail-safe systems will execute, whereupon the conditions necessary to invoke the other fail-safe system will be prevented from arising.

[0166] The operation of the fail-safe systems **306, 308** will be described in more detail hereinbelow. As used herein, a fail-safe system is "triggered" upon occurrence of the conditions necessary to cause the fail-safe system to operate as described to short circuit the electrodes **310, 340.**

[0167] Turning to the second fail-safe system **308** in more detail, when heated to a threshold temperature, the meltable member **372** will flow to bridge and electrically connect the electrodes **310, 340.** The meltable member **372** thereby redirects the current applied to the device **300** to bypass the varistor **350** so that the current induced heating of the varistor **350** ceases. The fail-safe system **306** may thereby serve to prevent or inhibit thermal runaway without requiring that the current through the SVL device **300** be interrupted.

[0168] More particularly, the meltable member **372** initially has a first configuration as shown in **FIG. 10** such that it does not electrically couple the inner electrode **340** and the housing electrode **310** except through the head **344.** Upon the occurrence of a heat buildup event, the inner electrode **340** is thereby heated. The meltable member **372** is also heated directly and/or by the inner electrode **340.** During normal operation, the temperature in the meltable member **372** remains below its melting point so that the meltable member **372** remains in solid form. However, when the temperature of the meltable member **372** exceeds its melting point, the meltable member **372** melts (in full or in part) and flows by force of gravity into a second configuration different from the first configuration. When the device **300** is vertically oriented, the melted meltable member **372** accumulates in the lower portion of the chamber **304U** as a reconfigured meltable member (which may be molten in whole or in part). The reconfigured meltable member **372** bridges or short circuits the inner electrode **340** to the housing electrode **310** to bypass the varistor stack **351.** That is, a new direct flow path or paths are provided from the surface of the inner electrode **340** to the surfaces of the housing side wall **333** through the reconfigured meltable member **372.** According to some embodiments, at least some of these flow paths do not include the varistor stack **351.**

[0169] The reconfigured meltable member **372** is typically contained in the chamber **304U.** The molten meltable member **372** is contained on the upper end by the compression member **348.** The molten meltable member **372** is contained on the lower end by the head **344,** the flange **334** and the membrane **370.** The barrier flange **366B** can prevent the meltable member **372** from flowing into the lower chamber **304L** and into the varistor stack **351.**

[0170] According to some embodiments, the second fail-safe system **308** can be triggered by at least two alternative triggering sets of operating conditions, as follows.

[0171] The second fail-safe system **308** can be triggered by heat generated in a varistor **350** by excessive leakage current. More particularly, when the voltage across the varistor **350** exceeds the nominal clamping voltage VNOM, a leakage current will pass through the varistor **350** and generate heat therein from ohmic losses. This may occur because the VNOM has dropped due to varistor **350** aging and/or because the voltage applied by the circuit across the device **300** has increased.

[0172] The second fail-safe system **308** can also be triggered when a varistor **350** fails as a short circuit. In this case, the varistor **350** will generate heat from a fault current through the short circuit failure site (*e.g.*, a pinhole in the varistor). The fault current generates heat (from high localized ohmic loss heating at the pinhole) in and adjacent the varistor **350.** As discussed below, a fail-short varistor may trigger the first fail-safe system **306** instead of the second fail-safe system **308,** depending on the magnitude of the fault current and other conditions.

[0173] With reference to **FIG. 15,** the first fail-safe system **306** can be triggered when a varistor **350** fails as a short circuit. In this case, arcing will occur adjacent and within a short circuit failure site in the varistor **350** (*i.e.,* the arc is initiated at the varistor **350).** More particularly, the arcing **FA** will occur between the varistor **350** or an interconnect member **354** and one or both electrodes **310, 340.** The arcing will propagate along the head **344** and, in some cases, the varistor stack **353.** Ultimately, the arcing propagates or occurs directly between the outer peripheral side wall **344B** of the electrode head **344** and the adjacent side surface **334B** of the flange **334.** This latter arcing causes a metal surface portion of the head side wall **344B** and a metal surface portion of the flange side wall **334B** to fuse or bond directly to one another in a prescribed region at a bonding or fusing site **306E** to form a bonded or fused interface portion, or region **306F.** The arc **FA** fuses or bonds the surfaces and portions **334B, 344B.** In some embodiments, the electrodes **310, 340** are both formed of aluminum or aluminum alloy, so that the bond is direct aluminum-to-aluminum, which can provide particularly low ohmic resistance. The fusing or bonding may occur by welding induced by the arc. In this way, the electrodes **310, 340** are shorted at the interface **306F** to bypass the varistors **350** so that the current induced heating of the failed varistor **350** ceases.

[0174] The electrical insulation membrane **370** is provided between the flange side surface **334B** and the electrode head **344** to provide electrical isolation in normal operation. However, the membrane **370** is formed of a material that is quickly disintegrated, melted or vaporized by the arcing so that the membrane **370** does not unduly impede the propagation of the arc or the bonding of the electrodes **310, 340** as described.

[0175] The void **G2** above the flange **334** around the inner electrode **340** in the chamber **304U** provides a break between the adjacent surfaces of the inner electrode **340** and the housing electrode **310** to extinguish the electric arc (*i.e,* to prevent the arc from continuing up the side wall **333).** The void **G2** reduces the time required to terminate the arc and facilitates more rapid formation of the bonded interface **306F.**

[0176] In the event of a fail-short varistor, either or both first and second fail-safe systems **306, 308** may be triggered or activated. The first fail-safe system **306** requires a fault current sufficient to create the arcing, whereas the second fail-safe system **308** does not. When sufficient fault current is present to create the arcing, the first fail-safe system **306** will typically execute and form the electrode short circuit before the second fail-safe system **308** can form the meltable member short. However, if the applied current is insufficient to generate the arcing, the fault current will continue to heat the device **300** until the second fail-safe system **308** is activated. Thus, where a fail-short varistor is the trigger, the second fail-safe system **308** will operate for relatively low current and the first fail-safe system **306** will operate for relatively high current.

[0177] Thus, the meltable member **372** and the fused interface **306F** each provide a direct electrical contact surface or a low resistance bridge between the inner electrode **340** and the housing electrode **310** and an enlarged current flow path (*i.e.*, a lower resistance short circuit) via the meltable member **372** or the fused site **306F.** In this way, the fault or leakage current is directed away from the varistor stack **351.** The arcing, ohmic heating and/or other phenomena inducing heat generation are diminished or eliminated, and thermal runaway and/or excessive overheat of the SVL module **300** can be prevented. The SVL module **300** may thereby convert to a relatively low resistance element capable of maintaining a relatively high current safely (*i.e,* without catastrophic destruction of the device). The fail-safe systems **306, 308** can thus serve to protect the SVL module **300** from catastrophic failure during its end of life mode. The present invention can provide a safe end of life mechanism for a varistor-based overvoltage device. It will be appreciated that the SVL module **300** may be rendered unusable thereafter as an overvoltage protection device, but catastrophic destruction (*e.g.*, resulting in combustion temperature, explosion, or release of materials from the SVL module 300) is avoided.

[0178] According to some embodiments, the meltable member **372** bypass and the fused interface **306F** bypass each have an ohmic resistance of less than about 3 mOhm.

[0179] In some embodiments, the SVL module **300** may be effectively employed in any orientation. For example, the SVL module **300** may be deployed in a vertical orientation or a horizontal orientation. When the meltable member **372** is melted by an overheat generation event, the meltable member **372** will flow to the lower portion of the chamber **304U** where it forms a reconfigured meltable member (which may be molten in whole or in part) that bridges the inner electrode **340** and the housing electrode **310** as discussed above. The chamber **304U** is sealed so that the molten meltable member **372** does not flow out of the chamber **304U.**

[0180] The external elastomeric insulating cover sleeve **376** serves to increase the insulation between the SVL module **300** and adjacent devices and to increase the creepage and air clearance distances.

[0181] During use, the varistor wafers may be damaged by overheating and may generate arcing inside the SVL housing assembly **311.** The SVL housing assembly **311** can contain the damage (*e.g.*, debris, gases and immediate heat) within the SVL module **300,** so that the SVL module **300** fails safely. In this way, the SVL module **300** can prevent or reduce any damage to adjacent equipment (*e.g*., switch gear equipment in the cabinet) and harm to personnel. In this manner, the SVL module **300** can enhance the safety of equipment and personnel.

[0182] According to some embodiments, the biased electrodes (*e.g*., the electrodes **310** and **340)** apply a load to the varistors along the axis **V-V** in the range of from 5 kN to 100 kN depending on its surface area.

[0183] In alternative embodiments (not shown), the SVL module **300** may be modified to use biasing or loading means such as metal spring washers and separate sealing means such as elastomeric O-rings.

[0184] In the assembled SVL module **300,** the large, planar contact surfaces of the components **344, 350, 354, 322** can ensure reliable and consistent electrical contact and connection between the components during an overvoltage or surge current event. The head **344** and the end wall **322** are mechanically loaded against these components to ensure firm and uniform engagement between the mating contact surfaces.

[0185] According to some embodiments, the combined thermal mass of the housing (*e.g.*, the housing electrode **310)** and the electrode (*e.g.,* the electrode **340)** is substantially greater than the thermal mass of each of the varistors captured therebetween. The greater the ratio between the thermal mass of the housing and electrodes and the thermal mass of the varistors, the better the varistors will be preserved during exposure to surge currents and TOV events and therefore the longer the lifetime of the SVL. As used herein, the term "thermal mass" means the product of the specific heat of the material or materials of the object multiplied by the mass or masses of the material or materials of the object. That is, the thermal mass is the quantity of energy required to raise one gram of the material or materials of the object by one degree centigrade times the mass or masses of the material or materials in the object. According to some embodiments, the thermal mass of at least one of the electrode head and the electrode wall is substantially greater than the thermal mass of the varistor. According to some embodiments, the thermal mass of at least one of the electrode head and the electrode wall is at least two times the thermal mass of the varistor, and, according to some embodiments, at least ten times as great. According to some embodiments, the combined thermal masses of the head and the electrode wall are substantially greater than the thermal mass of the varistor, according to some embodiments at least two times the thermal mass of the varistor and, according to some embodiments, at least ten times as great.

[0186] With reference to **FIGS. 16** and **17,** an SVL module **400** according to some embodiments is shown therein. According to some embodiments, each of the SVLs **P1, P2, P3** as discussed herein is constructed and operate as disclosed for the SVL module **400.**

[0187] The SVL module **400** includes a housing assembly **411,** a varistor stack **451,** an electrical insulator membrane **470,** a cover **476,** an insulation cap **478,** a first fail-safe mechanism **406** (which uses arc fusing), and a second fail-safe mechanism **408** (including a meltable member **472).** The components **411, 451, 470, 476, 478, 406, 408,** and **472** may be constructed and operate substantially in the same manner as the components **311, 351, 370, 376, 378, 306, 308,** and **372,** respectively, except as follows.

[0188] The module housing assembly **411** includes a one-piece lower housing electrode **410** instead of the two-piece lower housing electrode **310.** The varistor stack **451** includes varistors **450** arranged in electrical series instead of parallel. No electrical insulator stack assembly corresponding to the electrical insulator stack assembly **360** is provided. The electrical insulator membrane **470** surrounds the varistor stack **451** to insulate the varistors **450** from the electrode side wall **433.** The lower end of the electrical insulator membrane **470** coincides with the lower edge of the lowest varistor **450** of the stack **451.**

[0189] With reference to **FIG. 18,** a single-point sheath bonding or overvoltage/induced current control system **550** according to some embodiments is shown therein. The sheath bonding system **550** may be incorporated into the power generation system **100** as illustrated in **FIG. 1** to form an alternative power generation system **500** in accordance with some embodiments. The sheath bonding system **550** includes three of the SVLs **P1, P2, P3** as disclosed hereinabove.

[0190] In the sheath bonding system **550,** the first ends **141A, 142A, 143A** of the cable sheaths **141, 142** and **143** are each solidly bonded to ground, as illustrated in **FIG. 18.**

[0191] Also, in the sheath bonding system **550,** the opposing second ends **141B, 142B, 143B** of the cable sheaths **141, 142** and **143** are each connected to ground through the SVLs **P1, P2** and **P3,** respectively. As discussed above with regard to the cross-bonding sheath bonding system **150,** the sheaths **141, 142, 143** are connected to ground only indirectly or selectively. That is, the SVLs **P1, P2, P3** do not directly bond the sheaths **141, 142, 143** to ground.

[0192] The SVLs **P1, P2, P3** electrically isolate the ends **141B, 142B, 143B** of the sheaths **141, 142, 143** from ground except in response to conditions that cause the SVLs to conduct. More particularly, the varistor **215** of each SVL **P1, P2, P3** electrically insulates the sheaths from ground or electrically connects the sheaths to ground, depending on the conditions of the system and the state of the varistor **215.** Additionally, each SVL **P1, P2, P3** has a fail-safe system **217** that causes the SVL **P1, P2, P3** to short or connect the associated sheaths to ground in response to some conditions or events. Each fail-safe system **217** may include multiple fail-safe mechanisms that respond to different conditions or events.

[0193] In use, the SVLs **P1, P2, P3** will respond to the different operating conditions of or voltage events on the sheaths **141, 142, 143** in the same manner as described for the cross-bonding sheath bonding system **150,** and will protect the cables **131, 132, 133** in the same manner.

[0194] The sheath bonding system **550** may include a link box including the SVLs **P1, P2, P3,** a housing containing the SVLs, and associated connectors. However, the link box of the sheath bonding system **550** will not include cross-connection interconnects.

[0195] Embodiments of the single point bonding configuration may be illustrated by way of example. In the single point bonding configuration, configuration the sheaths of one end of the cable are directly earthed and the sheaths at the other end of the cable are not earthed or they are earthed through SVLs (either way not directly earthed). These SVLs traditionally do not conduct at steady state or faults such as short-circuits (power frequency faults - 50Hz or 60HZ, depending on the power system). These sheath voltage limiters protect the cable jacket only during TOV events (e.g., lightning, etc.) from induced overvoltages.

[0196] SVLs according to some embodiments of the inventive concept conduct during power frequency faults (i.e., short circuits) protecting the cable jacket from the induced overvoltages during these faults. To do that they have a lower maximum continuous operating voltage (U_c) and by extension a lower residual voltage. That means that during lightning events the SVL according to some embodiments of the inventive concept has the ability to better protect the cable jacket as it is stressed less due to the lower residual voltage.

[0197] To illustrate the differences between the traditional SVLs and the SVLs according to embodiments of the inventive concept, a simulation of a MV cable has been performed. This cable has the following characteristics:

- The 30kV line comprises of 3 single-core cables in trefoil formation (500m).
- The cable is single-core (SC) cable of type A2X(FL)2Y, 18/30 (36) kV, 3x800 mm^2 with aluminum conductors, XLPE main insulation, Al-PE sheath and HDPE jacket.
- A nominal power of the line of 10MW is assumed.
- The single-phase short-circuit of the line is assumed to be 1.5kA.

[0198] The cable configuration is shown in **FIG. 27.**

[0199] As shown in **FIGS. 28** - **30,** the voltage of the unearthed end of the line and the included voltages and currents across the cable line (0m - Wind/ Solar Park & 500m - Substation) show that during steady state both kinds of SVLs do not conduct.

[0200] The differences between the two types of SVLs become apparent during faults. FIGS. 31 and 32 illustrate the sheath induced voltages of a traditional SVL and FIGS. 33 and 34 illustrate the sheath induced voltages on an SVL according to some embodiments of the inventive concept. The first fault that is simulated is a single - phase short - circuit of 1.5kA. The short - circuit takes place at the earthed side. The clamping Voltage on the SVL according to some embodiments of the inventive concept (FIGS. 33 and 34) results in 60% reduced stress on the Jacket As shown in **FIGS. 31 - 34,** traditional SVLs do not conduct during the single - phase short - circuit and so a large overvoltage appears. The SVLs according to some embodiments of the inventive concept conduct during the short - circuit event and the overvoltage that appears is limited. The voltage is reduced by 60% (830V_{rms} difference - from 1369V_{rms} to 542V_{rms}).

	Maximum Induced Sheath Voltage [V]
Traditional SVL	1369
SVL according to inventive concept	542

[0201] Embodiments of the inventive concept may provide SVLs that are configured to protect cable line sheaths, such as sheaths used on medium voltage cable lines (5 kV - 36 kV), from both TOV events, such as lightning strikes, along with power frequency faults, such as short circuits. The sheath induced voltage is influenced by the bonding configuration of the cable line. A special bonding configuration is used to reduce or minimize the induced sheath voltages and circulating currents. The selection of SVLs is done carefully, considering the sheath-induced voltage during steady state. The SVL is designed with a maximum continuous operating voltage that exceeds the steady state voltage to ensure non-conduction during that state. In some embodiments, the SVL is configured to have a residual voltage and MCOV that is less than a minimum induced voltage generated during a power frequency fault, but greater than the nominal operating voltage on the medium voltage cable, which may be, for example, about 5kV to about 36 kV. During transient overvoltage events such as lightning strikes (TOV events) or single-phase short circuits (power frequency faults), the SVL limits the overvoltage by conducting from the sheath to ground. It effectively clamps the overvoltage, reducing it to the level of the SVL residual voltage. This protective measure is used to safeguard both the cable jacket and the cable accessories from potential damage due to overvoltages.

[0202] Furthermore, the SVL serves an additional function by providing a conductive path to ground. In the case of a lightning transient, this grounding path offers protection to the entire length of the cable by preventing or reducing the propagation of travelling waves. The SVL according to embodiments of the inventive concept may have a withstand energy associated therewith. When the energy associated with a TOV event (e.g., lightning strike) or power frequency fault is lower than the withstand energy of the SVL, the SVL device clamps the voltage and recovers. The SVL device can handle a substantial of these events without failing. In some embodiments, the withstand characteristic of each SVL circuit is 33 kA applied in a 10/350μs profile.

[0203] If the energy of the TOV events or faults or the accumulated degradation caused by substantial TOV or fault events surpasses the withstand capability of the SVL device, then the SVL shorts to ground permanently.

[0204] While embodiments of the inventive concept have been described herein with respect to MV cable applications, similar cable cross-bonding arrangements may be used in high voltage (HV) cables. A short circuit type SVL with increased dimensions capable of withstanding higher energy can be used to protect HV cabling systems, such as those configured to carry 150kV, 275kV, 400kV, and the like. An SVL designed to operate only above the steady state or nominal voltage may practically critically decrease the jacket insulation due to reduced residual voltage because the maximum continuous operating voltage of the HV SVL will start conducting in any fault, surge or lightning event while it will not conduct during the steady state condition. Typical screen to ground withstand levels such as 20-30kV, 1.2/50us for >100kVrms HV systems (SVLs for Ur=10-18kVrms) may result in enhanced jacket insulation requirements, the latter can be reduced by using SVLs with Ur in the range of 100-500Vrms having residual voltage <3kVp.

[0205] Some aspects and embodiments of the present invention may be understood by reference to the following numbered clauses:

1. A sheath bonding system, comprising:
a link box comprising:

  a plurality of connectors configured to connect the link box with a plurality of transmission cables, each of the plurality of transmission cables including an inner conductor and a conductive sheath surrounding the inner conductor; and

  one or more sheath voltage limiter (SVL) circuits configured for connection to the plurality of connectors and an electrical ground, the one or more SVL circuits having a residual voltage that is less than a minimum induced voltage generated during a power frequency fault on one or more of the plurality of conductive sheaths, but greater than a nominal operating voltage on the one or more of the plurality of conductive sheaths.

2. The sheath bonding system of Clause 1, wherein the one or more SVL circuits has a maximum continuous operating voltage that is less than the minimum induced voltage generated during the power frequency fault on the one or more of the plurality of transmission cables, but greater than the nominal operating voltage on the one or more of the plurality of transmission cables.

3. The sheath bonding system of Clause 2, wherein the maximum continuous operating voltage is about 10% greater than the nominal operating voltage on the one or more of the plurality of conductive sheaths.

4. The sheath bonding system of Clause 1, wherein the plurality of connectors are configured to connect the conductive sheaths of the respective ones of the plurality of cables to each other in a cross-connect arrangement.

5. The sheath bonding system of Clause 1, wherein the plurality of connectors are configured to connect the conductive sheaths to the one or more SVL circuits in a single point bonding arrangement.

6. The sheath bonding system of Clause 1, wherein the plurality of transmission cables are configured to operate as medium voltage power cables.

7. The sheath bonding system of Clause 6, wherein medium voltage is in a range of about 5 kV to about 36 kV.

8. The sheath bonding system of Clause 1, wherein the one or more SVL circuits each has a withstand energy characteristic associated therewith; and
wherein each of the SVL circuits is configured to non-destructively process a power frequency fault or a transient overvoltage event when the power frequency fault or the transient overvoltage event does not exceed the withstand energy characteristic of the respective SVL circuit.

9. The sheath bonding system of Clause 8, wherein the withstand characteristic of each of the one or more SVL circuits is 33 kA applied in a 10/350μs profile.

10. The sheath bonding system of Clause 1, wherein the plurality of transmission cables are arranged in a trefoil formation.

11. The sheath bonding system of Clause 1 wherein the one or more SVL circuits comprise one or more varistors.

12. The surge protective device of Clause 1, wherein each of the one or more varistors includes a first fail-safe system and a second fail-safe system.

13. The sheath bonding system of Clause 12, wherein the first fail-safe system is configured to arc in response to current received through the respective varistor.

14. The sheath bonding system of Clause 12, wherein the second fail-safe system is configured to operate in response to heat generated by current received through the respective varistor.

15. The sheath bonding system of Clause 14, wherein the second fail-safe system comprises a meltable member.

16. The sheath bonding system of Clause 1, wherein the minimum induced voltage generated during a power frequency fault is about 500 - 1000 volts.

17. The sheath bonding system of Clause 16, wherein the residual voltage is in a range of about 80% - 90% of the minimum induced voltage generated during the power frequency fault.

18. The sheath bonding system of Clause 1, wherein the plurality of transmission cables are configured to operate as high voltage power cables.

19. The sheath bonding system of Clause 19, wherein high voltage is in a range of about 150 kV to about 400 kV.

20. A sheath bonding system, comprising:

a plurality of transmission cables, each of the plurality of transmission cables including an inner conductor and a conductive sheath surrounding the inner conductor; and
one or more sheath voltage limiter (SVL) circuits configured for connection to the plurality of transmission cables and an electrical ground, the one or more SVL circuits having a residual voltage that is less than a minimum induced voltage generated during a power frequency fault on one or more of the plurality of conductive sheaths, but greater than a nominal operating voltage on the one or more of the plurality of conductive sheaths.

21. The sheath bonding system of Clause 1, wherein the one or more SVL circuits has a maximum continuous operating voltage that is less than the minimum induced voltage generated during the power frequency fault on the one

or more of the plurality of transmission cables, but greater than the nominal operating voltage on the one or more of the plurality of transmission cables.

22. The sheath bonding system of Clause 21, wherein the maximum continuous operating voltage is about 10% greater than the nominal operating voltage on the one or more of the plurality of conductive sheaths.

23. The sheath bonding system of Clause 20, wherein the conductive sheaths of the respective ones of the plurality of transmission cables are connected to each other in a cross-connect arrangement.

24. The sheath bonding system of Clause 20, wherein the conductive sheaths are connected to the one or more SVL circuits in a single point bonding arrangement.

25. The sheath bonding system of Clause 20, wherein the minimum induced voltage generated during a power frequency fault is about 500 - 1000 volts.

26. The sheath bonding system of Clause 25, wherein the residual voltage is in a range of about 80% - 90% of the minimum induced voltage generated during the power frequency fault.

27. A sheath bonding system, comprising:

a link box comprising a plurality of connectors;
a plurality of transmission cables, each of the plurality of transmission cables including an inner conductor and a conductive sheath surrounding the inner conductor;
a plurality of linking cables configured to connect the plurality of transmission cables to the plurality of connectors; and
one or more sheath voltage limiter (SVL) circuits configured for connection to the plurality of terminals and an electrical ground, the one or more SVL circuits having a residual voltage that is less than a minimum induced voltage generated during a power frequency fault on one or more of the plurality of conductive sheaths, but greater than a nominal operating voltage on the one or more of the plurality of conductive sheaths.

28. The sheath bonding system of Clause 27, wherein the plurality of conductive sheaths are sectionalized into sheath minor sections, the sheath bonding system further comprising:
a plurality of cable joints, respective ones of the plurality of cable joints being configured to electrically isolate adjacent ends of the sheath minor sections from one another.

29. The sheath bonding system of Clause 28, wherein the plurality of cable joints are further configured to electrically connect the plurality of linking cables to the sheath minor sections.

30. The sheath bonding system of Clause 27, wherein the plurality of connectors are configured to connect the conductive sheaths of the respective ones of the plurality of cables to each other in a cross-connect arrangement.

31. The sheath bonding system of Clause 27, wherein the plurality of connectors are configured to connect the conductive sheaths to the one or more SVL circuits in a single point bonding arrangement.

32. A power generation system, comprising:

an electrical power source;
a transmission grid;
a plurality of transmission cables configured to couple the electrical power source to the transmission grid, each of the plurality of transmission cables including an inner conductor and a conductive sheath surrounding the inner conductor; and
one or more sheath voltage limiter (SVL) circuits configured for connection to the plurality of transmission cables and an electrical ground, the one or more SVL circuits having a residual voltage that is less than a minimum induced voltage generated during a power frequency fault on one or more of the plurality of conductive sheaths, but greater than a nominal operating voltage on the one or more of the plurality of conductive sheaths.

33. The power generation system, further comprising:

a medium voltage transformer configured to couple the electrical power source to the plurality of transmission cables; and
generator cables that are configured to couple the medium voltage transformer to the electrical power source.

34. The power generation system of Clause 33, further comprising:

a medium voltage-to-high voltage transformer configured to couple the plurality of transmission cables to the transmission grid;
wherein the plurality of transmission cables are further configured to couple the medium voltage transformer to the medium voltage-to-high voltage transformer.

35. The power generation system of Clause 34, further comprising:
utility cables that are configured to couple the medium voltage-to-high voltage transformer to the transmission grid.

[0206] In an aspect of the invention, a surge protective device includes a link box including a plurality of connectors and one or more sheath voltage limiter (SVL) circuits. The plurality of connectors are configured to interface with a plurality of cables, each of the plurality of cables including an inner conductor and a conductive sheath surrounding the inner conductor. The one or more sheath voltage limiter (SVL) circuits is/are configured for connection to the plurality of terminals and an electrical ground, the one or more SVL circuits having a residual voltage that is less than a minimum induced voltage generated during a power frequency fault on one or more of the plurality of conductive sheaths, but greater than a nominal operating voltage on the one or more of the plurality of conductive sheaths.

[0207] Many alterations and modifications may be made by those having ordinary skill in the art, given the benefit of present disclosure, without departing from the spirit and scope of the invention. Therefore, it must be understood that the illustrated embodiments have been set forth only for the purposes of example, and that it should not be taken as limiting the invention as defined by the following claims. The following claims, therefore, are to be read to include not only the combination of elements which are literally set forth but all equivalent elements for performing substantially the same function in substantially the same way to obtain substantially the same result. The claims are thus to be understood to include what is specifically illustrated and described above, what is conceptually equivalent, and also what incorporates the essential idea of the invention.

Claims

1. A sheath bonding system (150, 550), comprising:
a link box (200-1, 200-1) comprising:

a plurality of connectors (J1-J3, K1-K3) configured to connect the link box with a plurality of transmission cables (131, 132, 133), each of the plurality of transmission cables including an inner conductor (135) and a conductive sheath (141, 142, 143) surrounding the inner conductor; and
one or more sheath voltage limiter (SVL) circuits (P1, P2, P3) configured for connection to the plurality of connectors and an electrical ground, the one or more SVL circuits having a residual voltage that is less than a minimum induced voltage generated during a power frequency fault on one or more of the plurality of conductive sheaths, but greater than a nominal operating voltage on the one or more of the plurality of conductive sheaths.

2. The sheath bonding system of Claim 1, wherein the one or more SVL circuits (P1, P2, P3) has a maximum continuous operating voltage that is less than the minimum induced voltage generated during the power frequency fault on the one or more of the plurality of transmission cables (131, 132, 133), but greater than the nominal operating voltage on the one or more of the plurality of transmission cables.

3. The sheath bonding system of Claim 2, wherein the maximum continuous operating voltage is about 10% greater than the nominal operating voltage on the one or more of the plurality of conductive sheaths (141, 142, 143).

4. The sheath bonding system of Claim 1, wherein the plurality of connectors are configured to connect the conductive sheaths (141, 142, 143) of the respective ones of the plurality of transmission cables to each other in a cross-connect arrangement.

5. The sheath bonding system of Claim 1, wherein the plurality of connectors are configured to connect the conductive sheaths (141, 142, 143) to the one or more SVL circuits (P1, P2, P3) in a single point bonding arrangement.

6. The sheath bonding system of Claim 1, wherein the one or more SVL circuits each has a withstand energy characteristic associated therewith; and
wherein each of the SVL circuits is configured to non-destructively process a power frequency fault or a transient overvoltage event when the power frequency fault or the transient overvoltage event does not exceed the withstand energy characteristic of the respective SVL circuit.

7. The sheath bonding system of Claim 6, wherein the withstand characteristic of each of the one or more SVL circuits is 33 kA applied in a 10/350μs profile.

8. The sheath bonding system of Claim 1, wherein the plurality of transmission cables are arranged in a trefoil formation.

9. The sheath bonding system of Claim 1 wherein the one or more SVL circuits comprise one or more varistors (350).

10. The surge protective device of Claim 1, wherein each of the one or more varistors includes a first fail-safe system (306) and a second fail-safe system (308);

wherein the first fail-safe system is configured to arc in response to current received through the respective varistor; and
wherein the second fail-safe system is configured to operate in response to heat generated by current received through the respective varistor.

11. The sheath bonding system of Claim 1 including
a plurality of linking cables (152) configured to connect the plurality of transmission cables (131, 132, 133) to the plurality of connectors (J1-J3, K1-K3).

12. The sheath bonding system of Claim 11, wherein the plurality of conductive sheaths (141, 142, 143) are sectionalized into sheath minor sections (141D, 141E, 141F, 142D, 142E, 142F, 143D, 143E, 143F), the sheath bonding system further comprising:
a plurality of cable joints (154), respective ones of the plurality of cable joints being configured to electrically isolate adjacent ends of the sheath minor sections from one another.

13. The sheath bonding system of Claim 12, wherein the plurality of cable joints are further configured to electrically connect the plurality of linking cables (152) to the sheath minor sections.

14. The sheath bonding system of Claim 11, wherein the plurality of connectors connect the conductive sheaths of the respective ones of the plurality of transmission cables (131, 132, 133) to each other in a cross-connect arrangement.

15. The sheath bonding system of Claim 11, wherein the plurality of connectors connect the conductive sheaths (141, 142, 143) to the one or more SVL circuits in a single point bonding arrangement.

16. A power generation system, comprising:

an electrical power source (110);
a transmission grid (124);
a plurality of transmission cables (131, 132, 133) configured to couple the electrical power source to the transmission grid, each of the plurality of transmission cables including an inner conductor (135) and a conductive sheath (141, 142, 143) surrounding the inner conductor; and
the link box (200-1, 200-2) of Claim 1;
wherein the plurality of transmission cables are connected to the link box by the plurality of connectors.

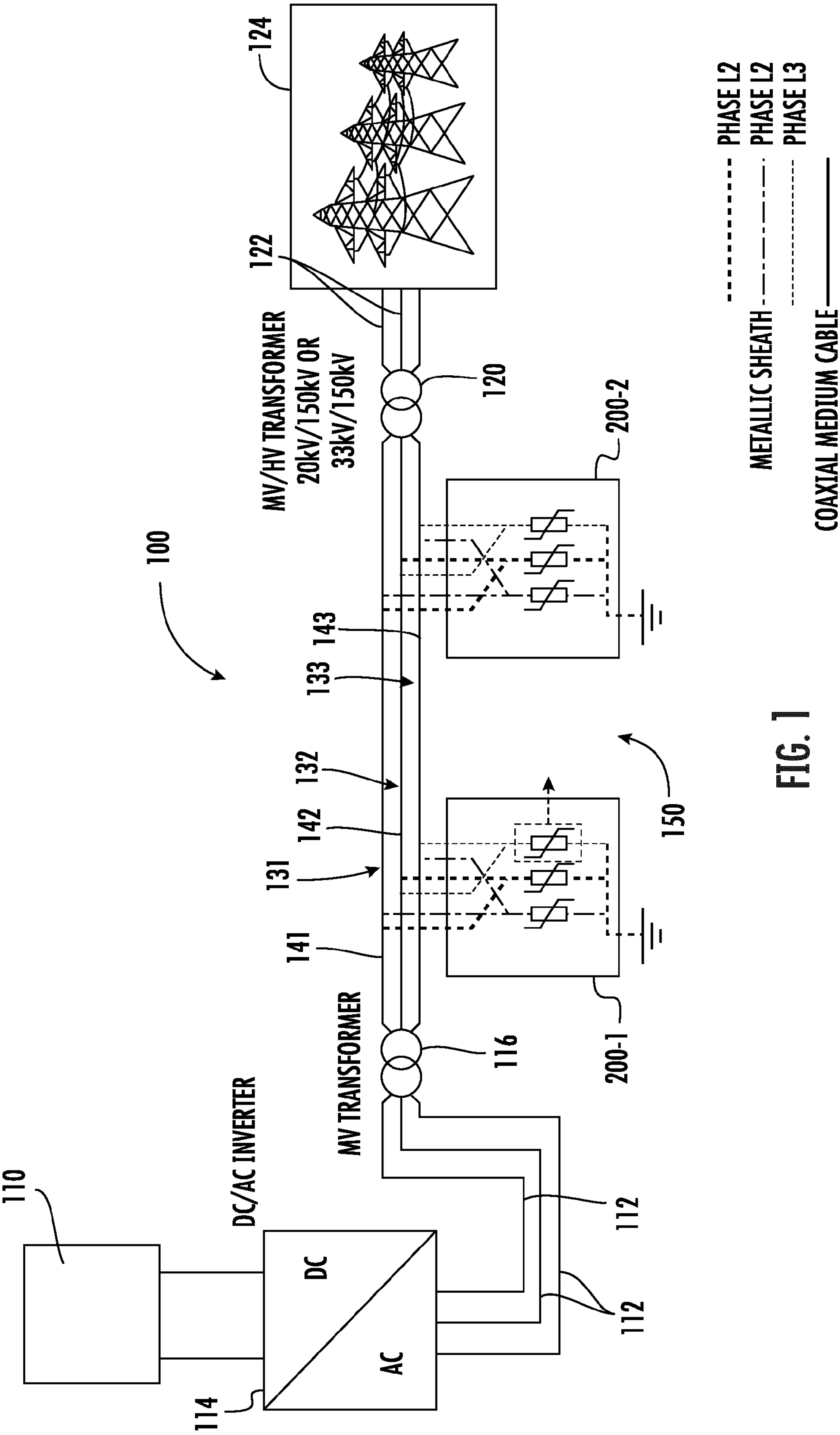

100
110
114
DC/AC INVERTER
DC
AC
112
112
MV TRANSFORMER
116
141
131
142
132
133
143
MV/HV TRANSFORMER
20kV/150kV OR
33kV/150kV
120
122
124
200-1
200-2
150
PHASE L2
PHASE L2
PHASE L3
METALLIC SHEATH
COAXIAL MEDIUM CABLE

FIG. 1

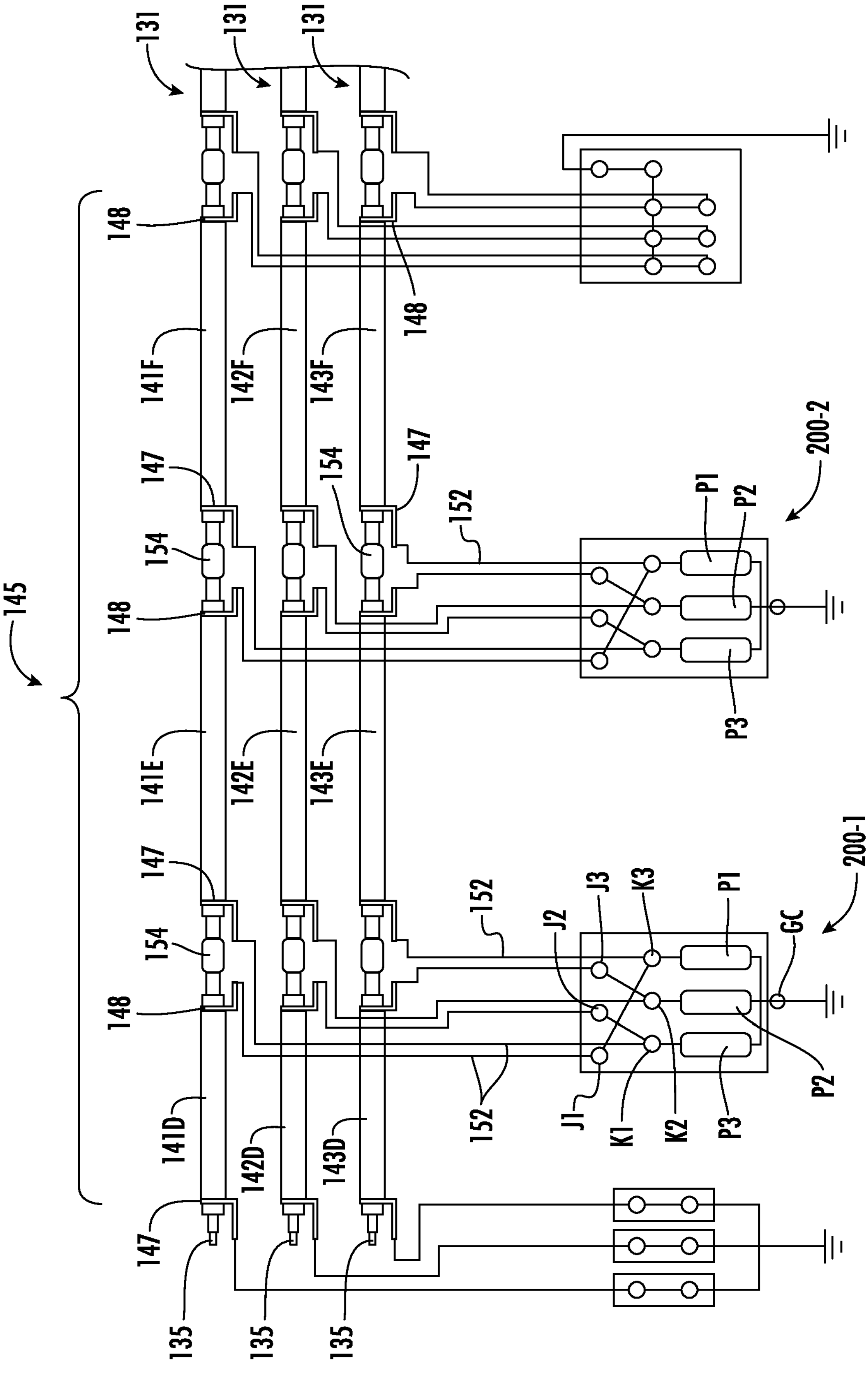

131
131
131
145
148
148
148
148
141F
142F
143F
147
147
147
147
154
154
154
152
152
152
200-2
200-1
P1
P2
P3
J1
J2
J3
K1
K2
K3
GC
141E
142E
143E
141D
142D
143D
135
135
135

FIG. 2

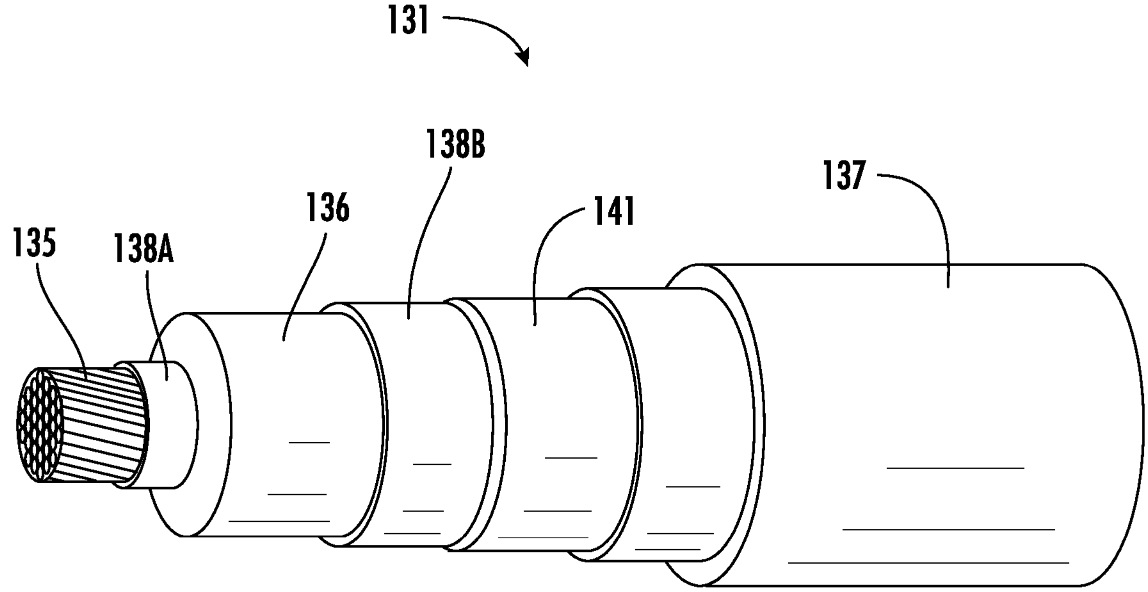


FIG. 3

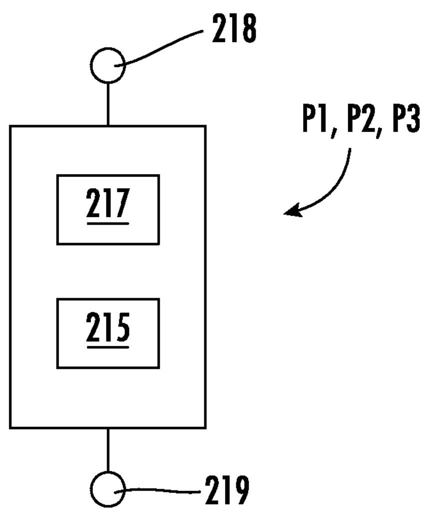


FIG. 4

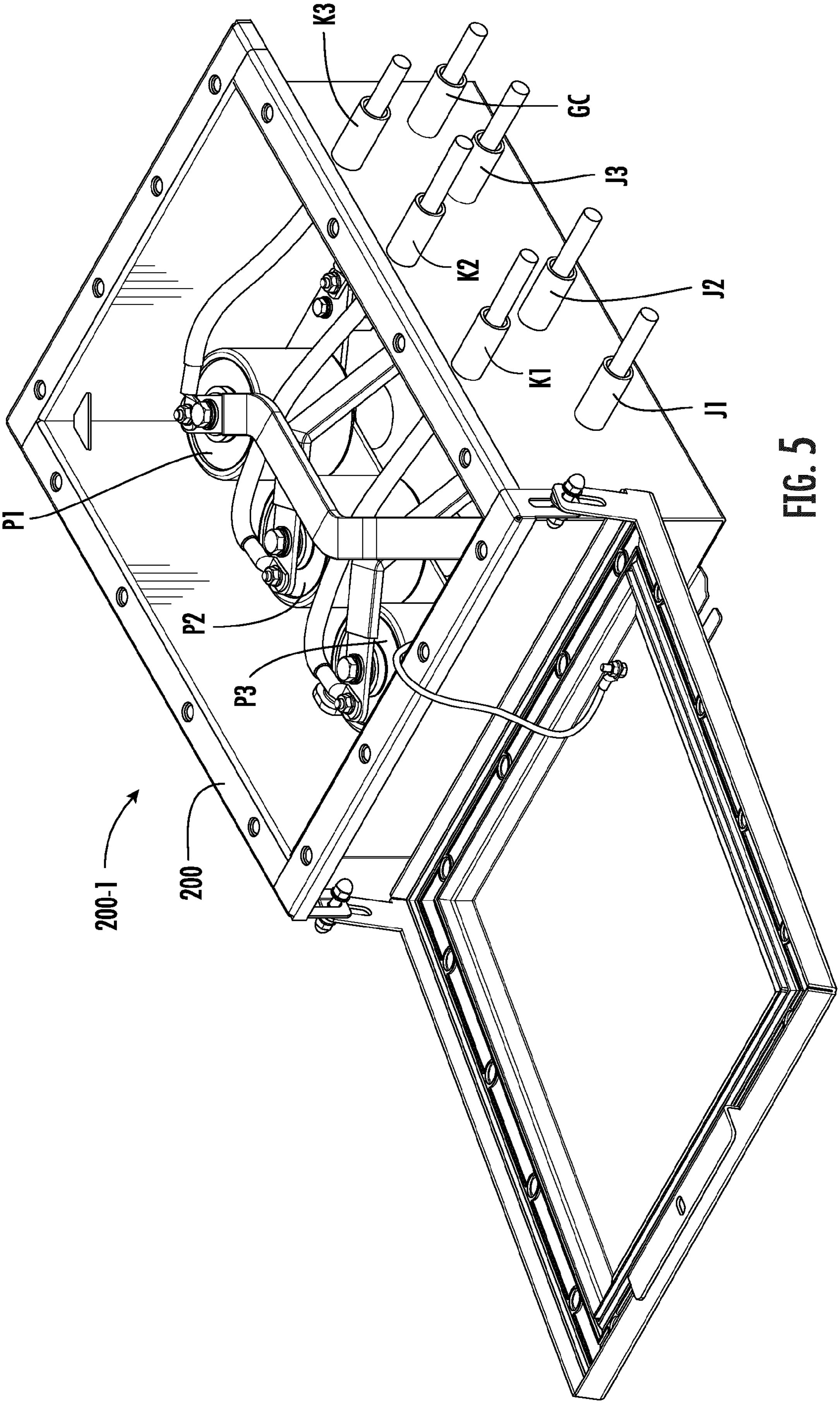


FIG. 5

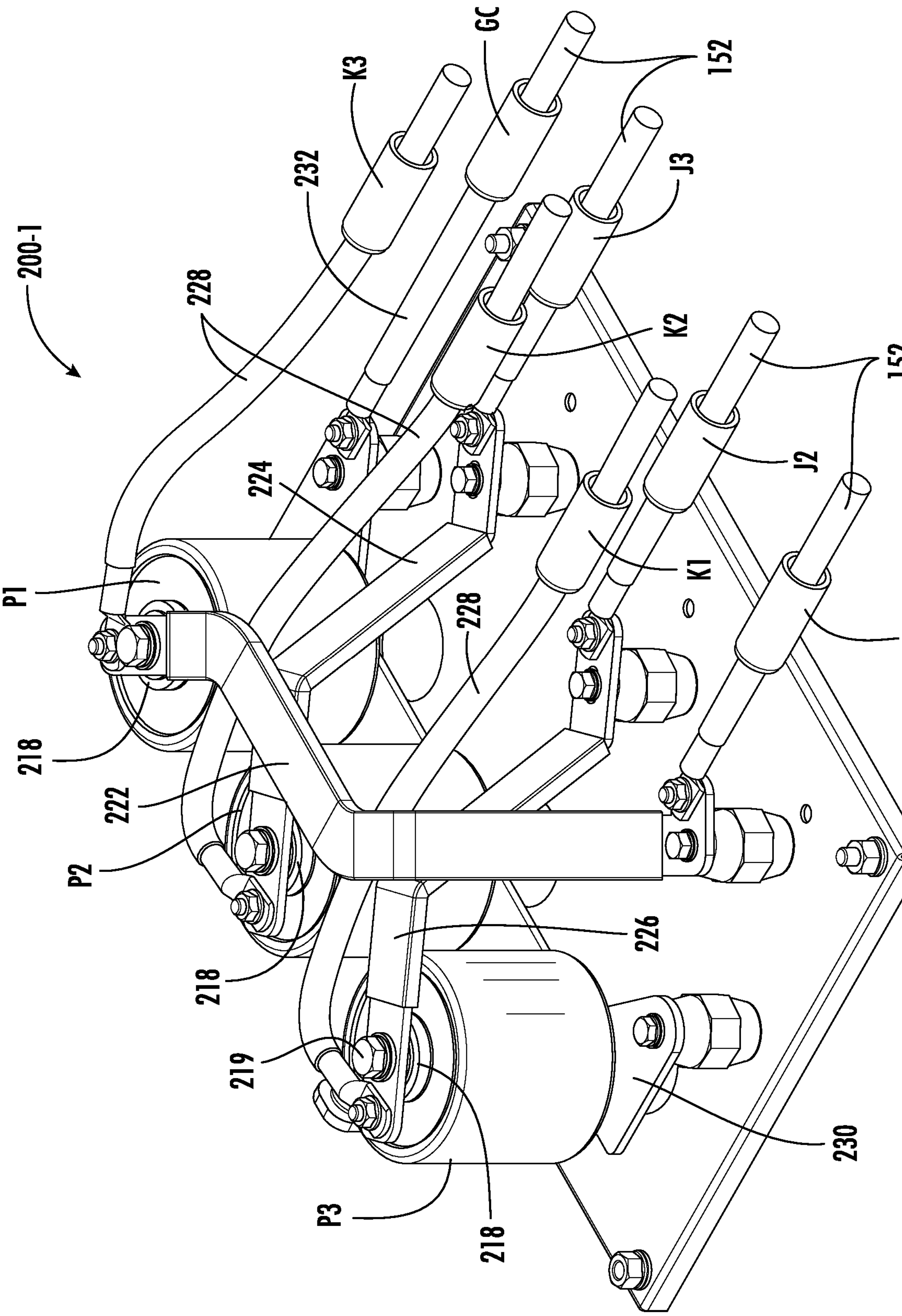

200-1
228
232
K3
GC
152
J3
K2
152
J2
J1
K1
228
224
P1
218
222
P2
226
218
219
218
P3
230

FIG. 6

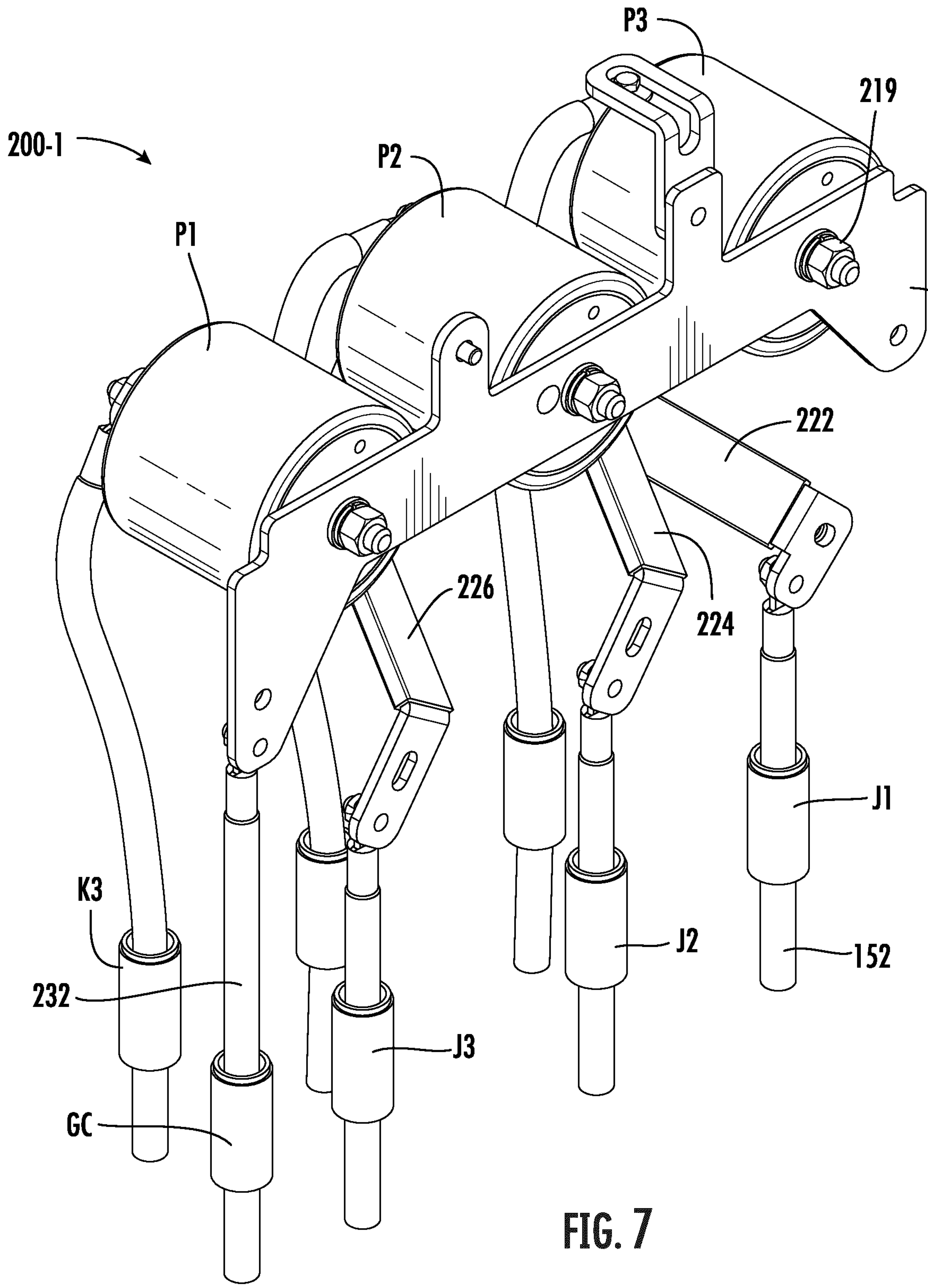


FIG. 7

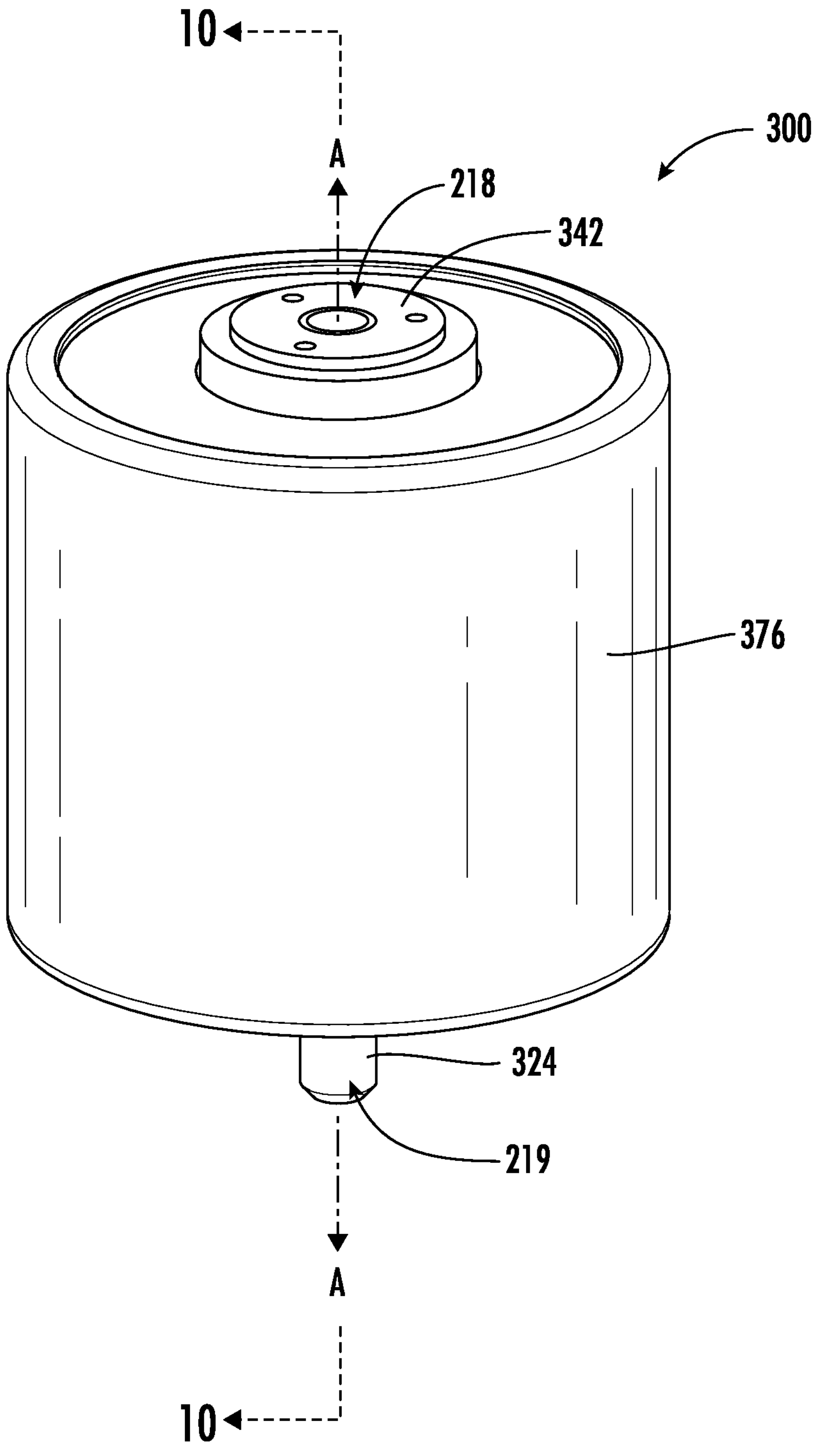


FIG. 8

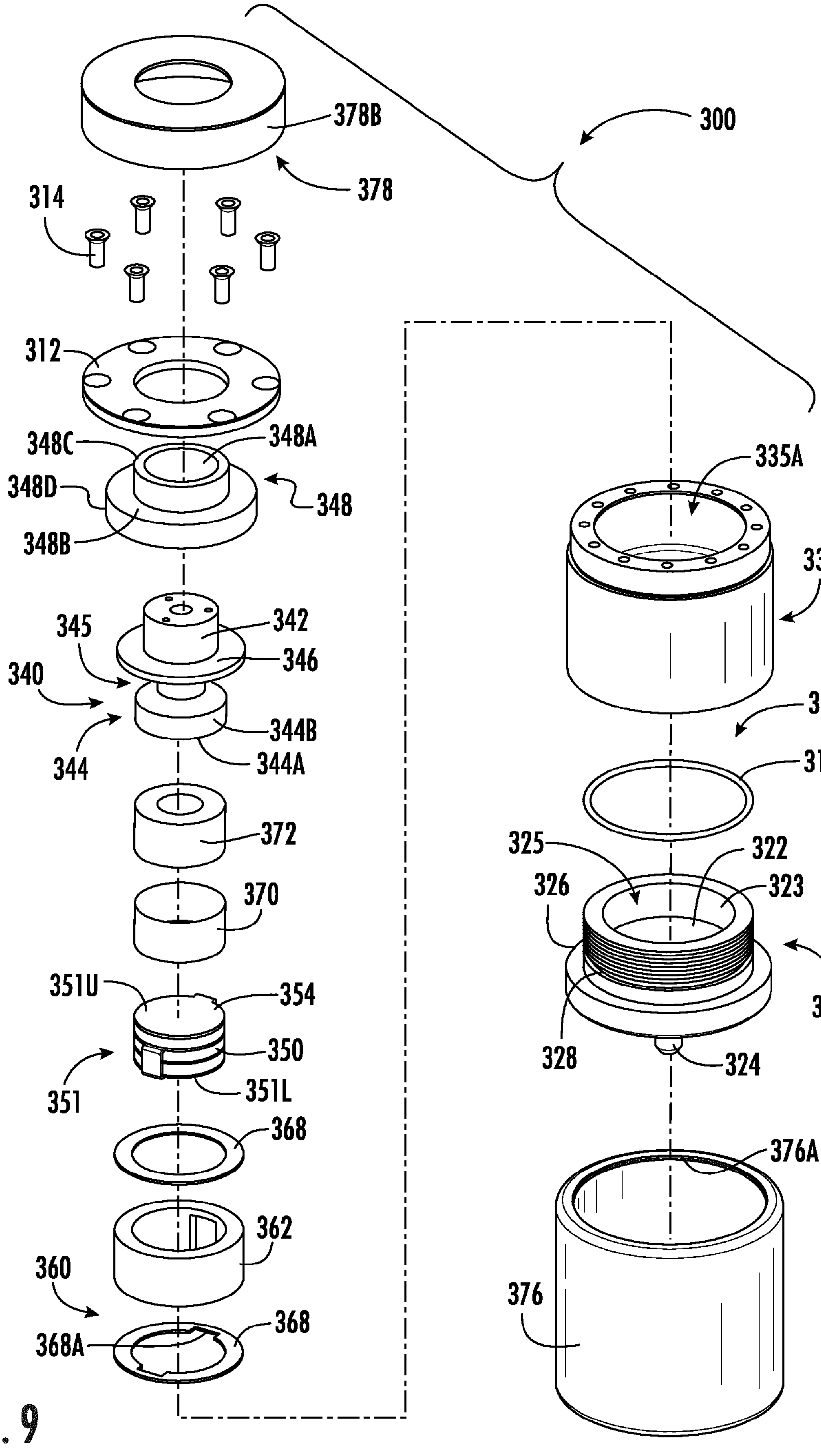

378B
300
378
314
312
348C
348A
348D
348
348B
330
335A
345
342
346
340
344B
344
344A
310
316
372
325
322
326
323
370
351U
354
320
350
328
324
351
351L
368
376A
362
360
376
368
368A

FIG. 9

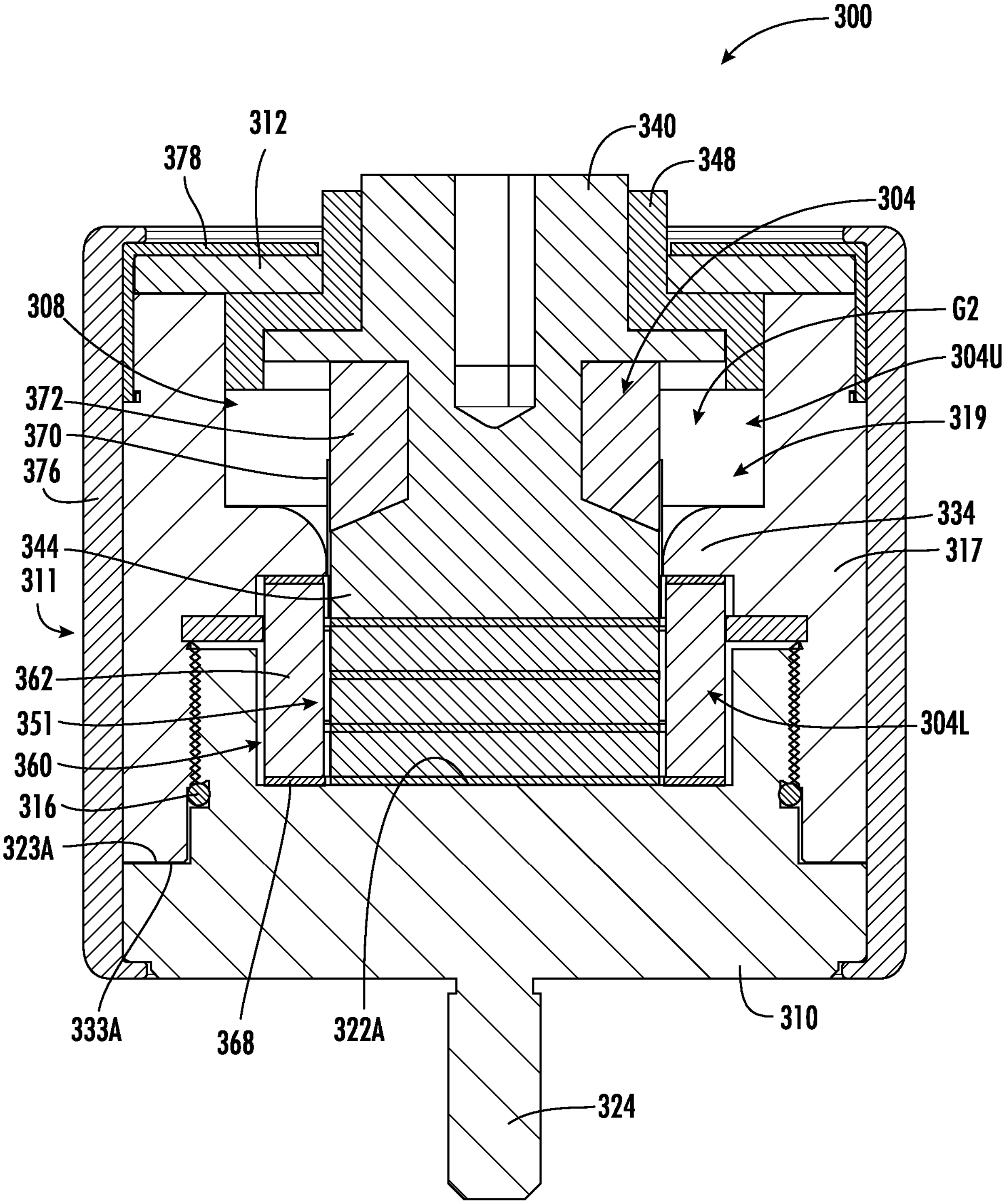

300
312
378
340
348
304
308
G2
304U
372
370
319
376
334
344
317
311
362
351
304L
360
316
323A
333A
368
322A
310
324

FIG. 10

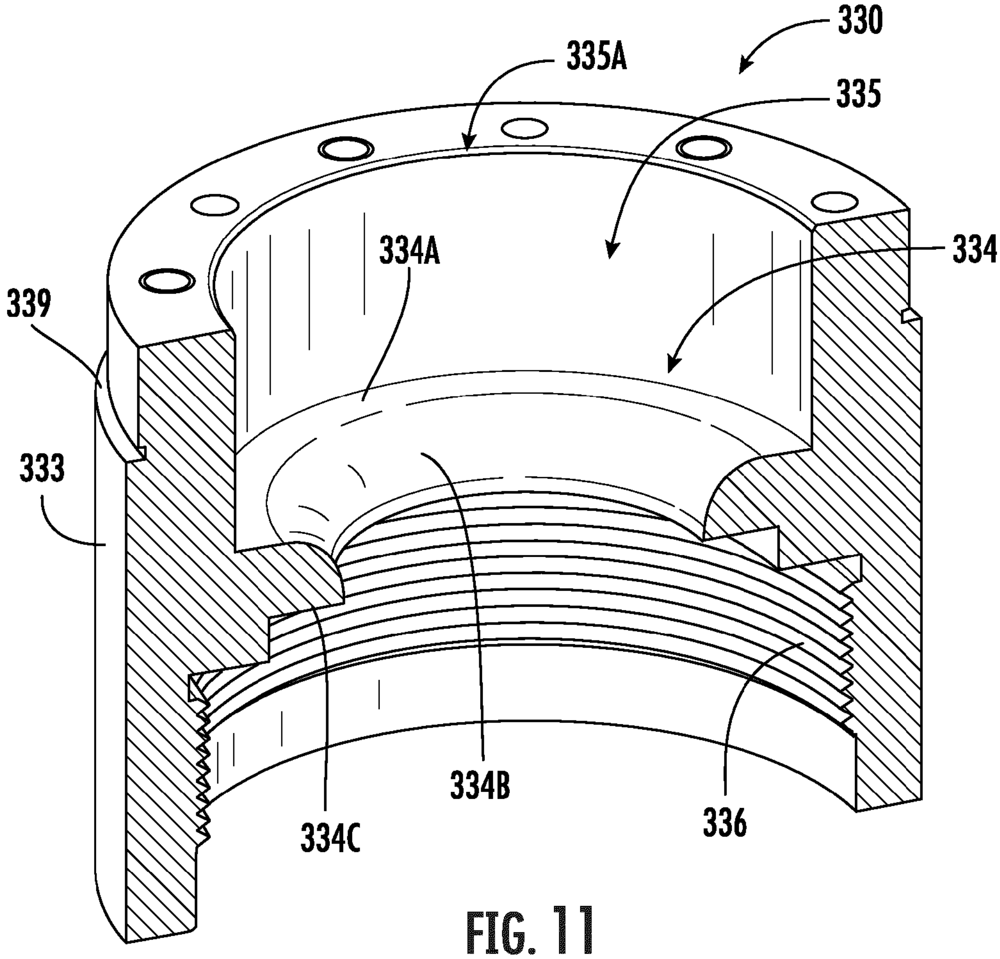

330
335A
335
334A
334
339
333
334C
334B
336

FIG. 11

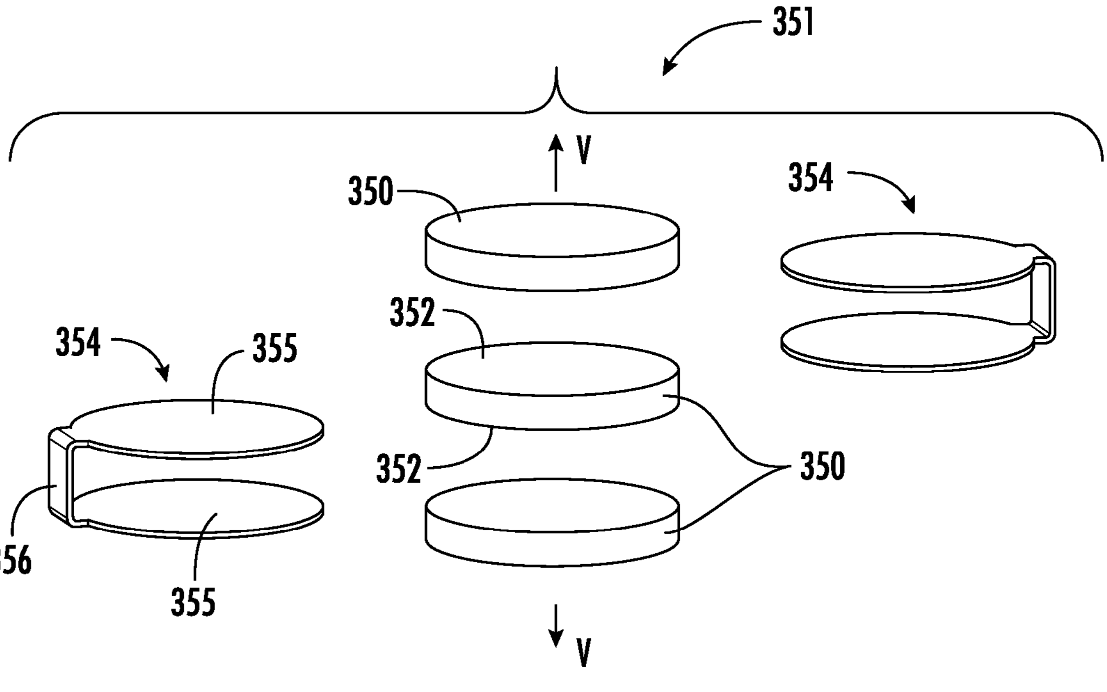

351
V
350
354
352
354
355
352
350
356
355
V

FIG. 12

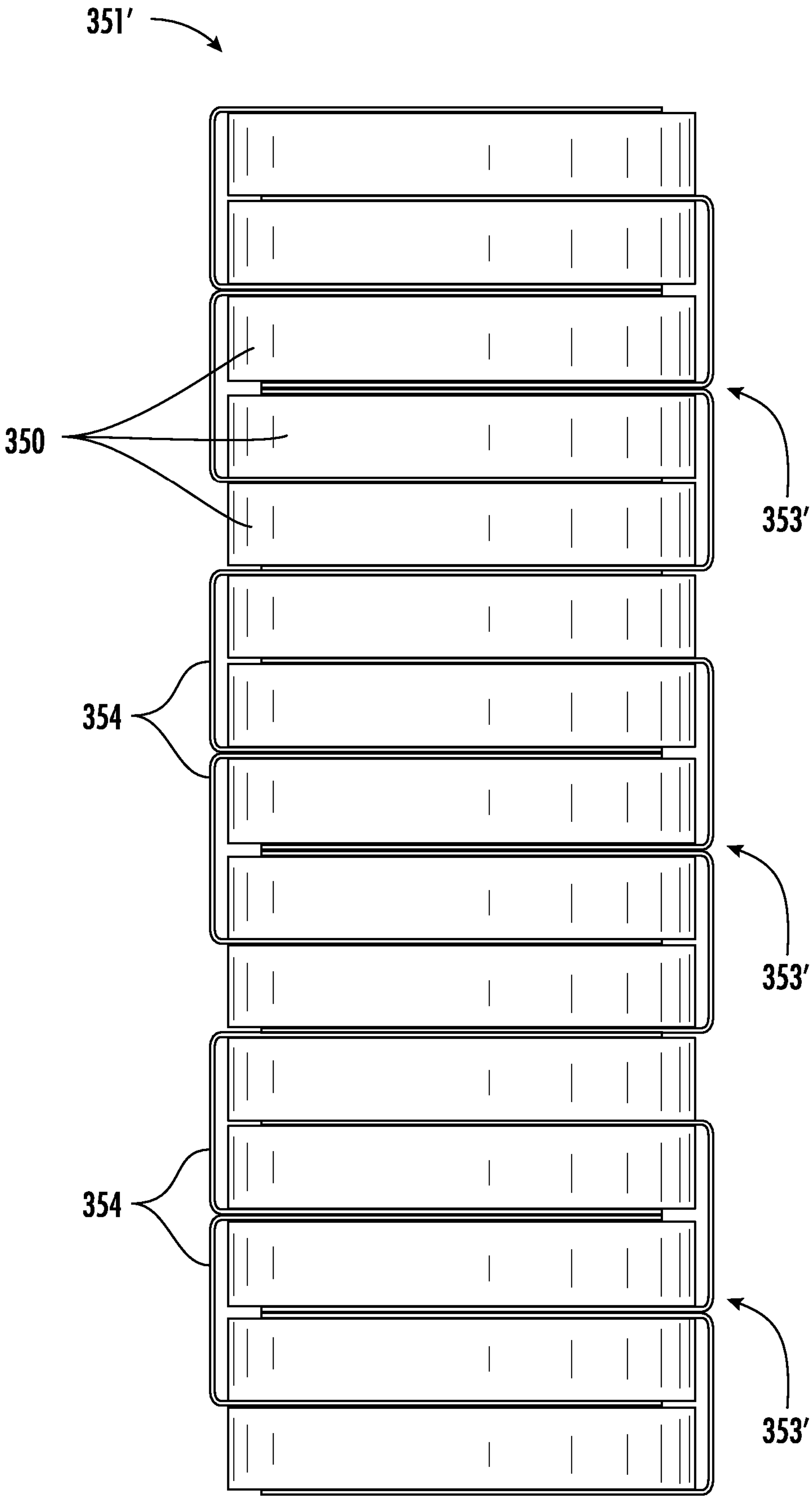


FIG. 13

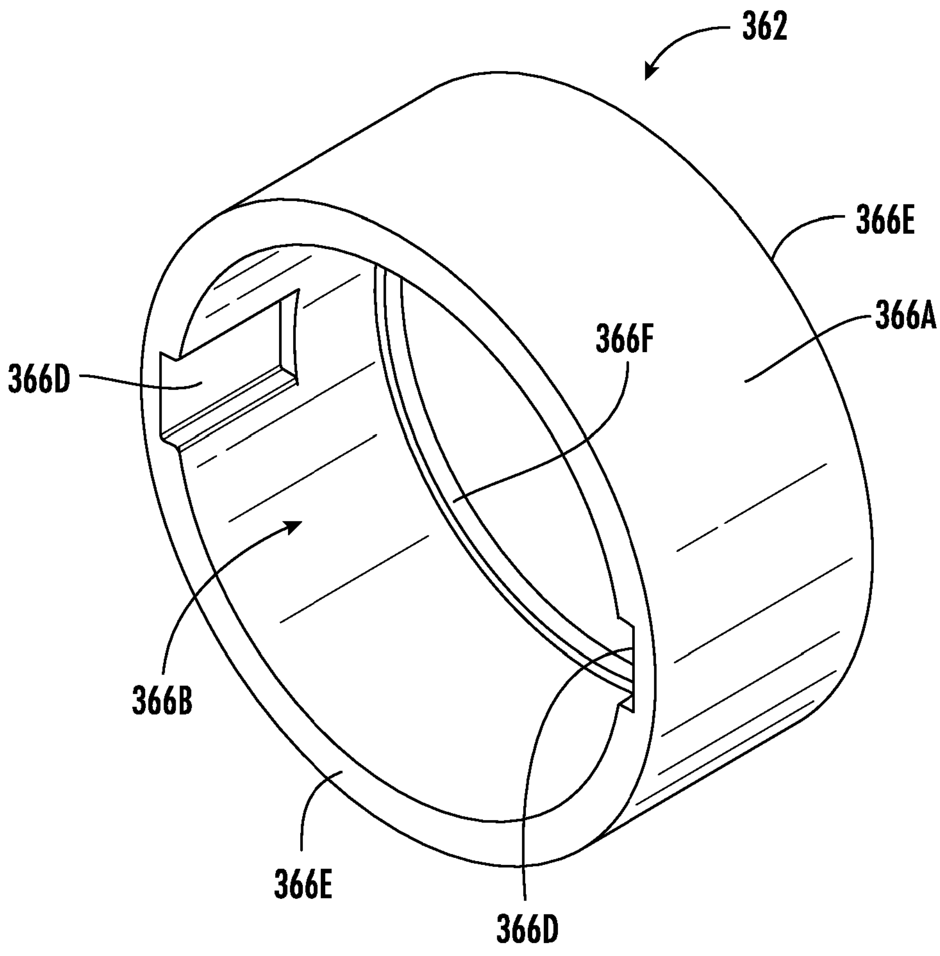


FIG. 14

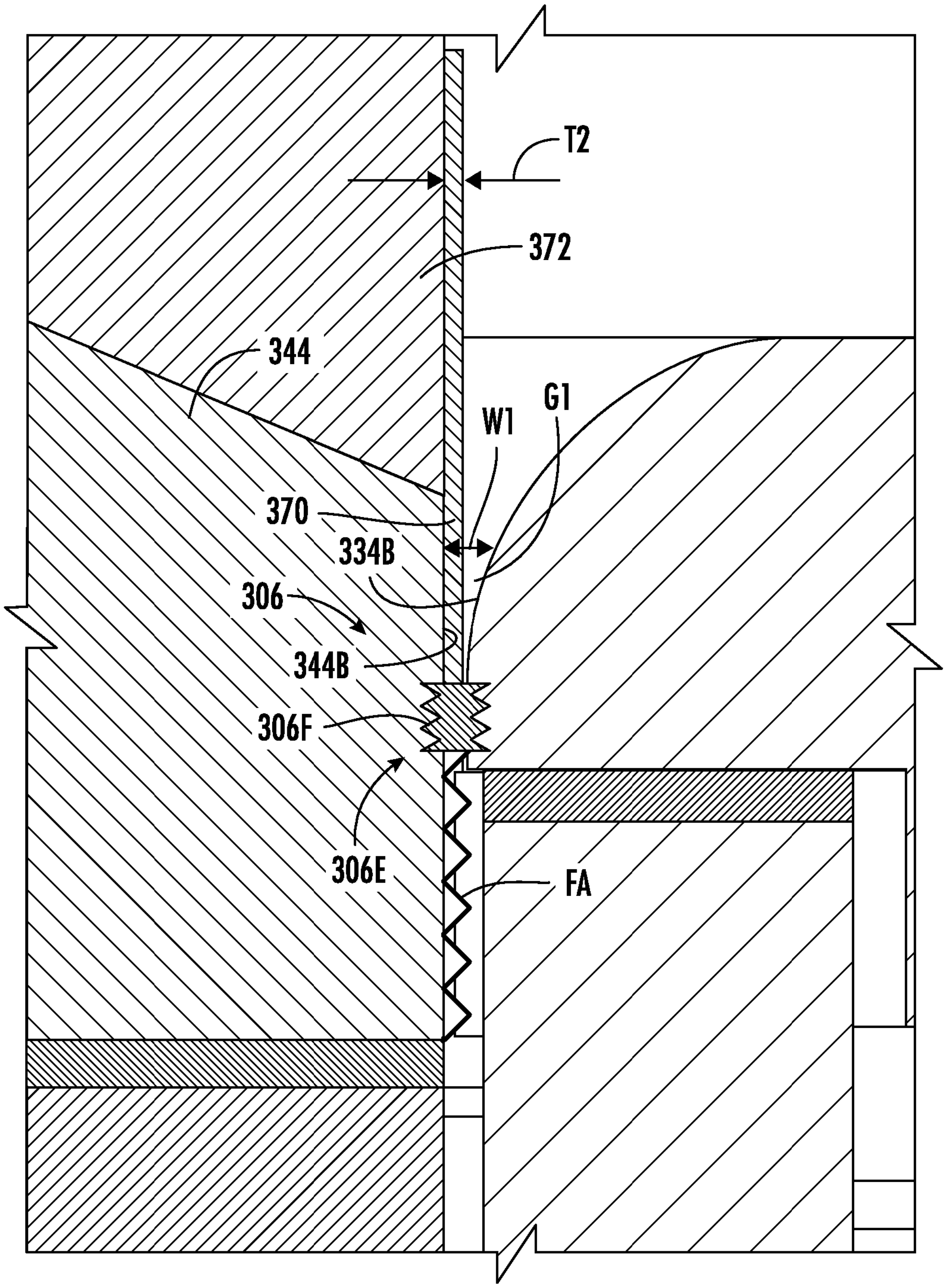


FIG. 15

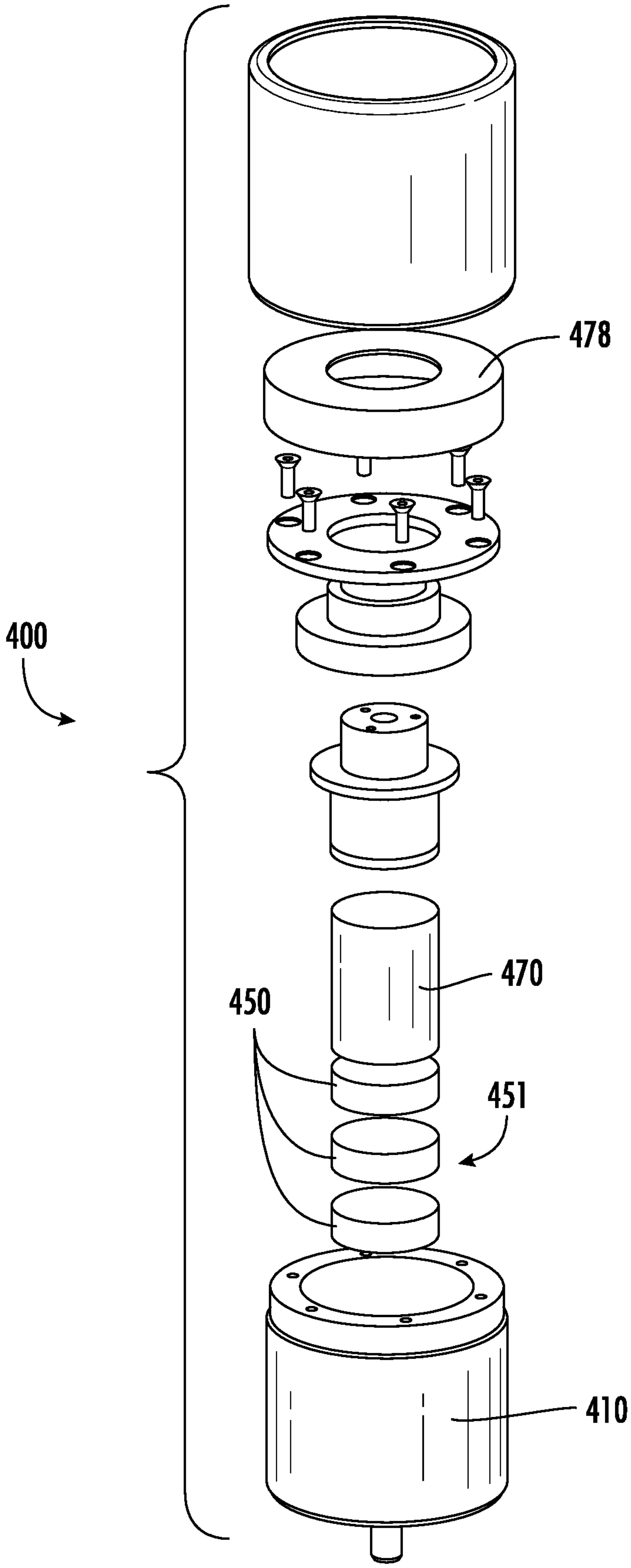


FIG. 16

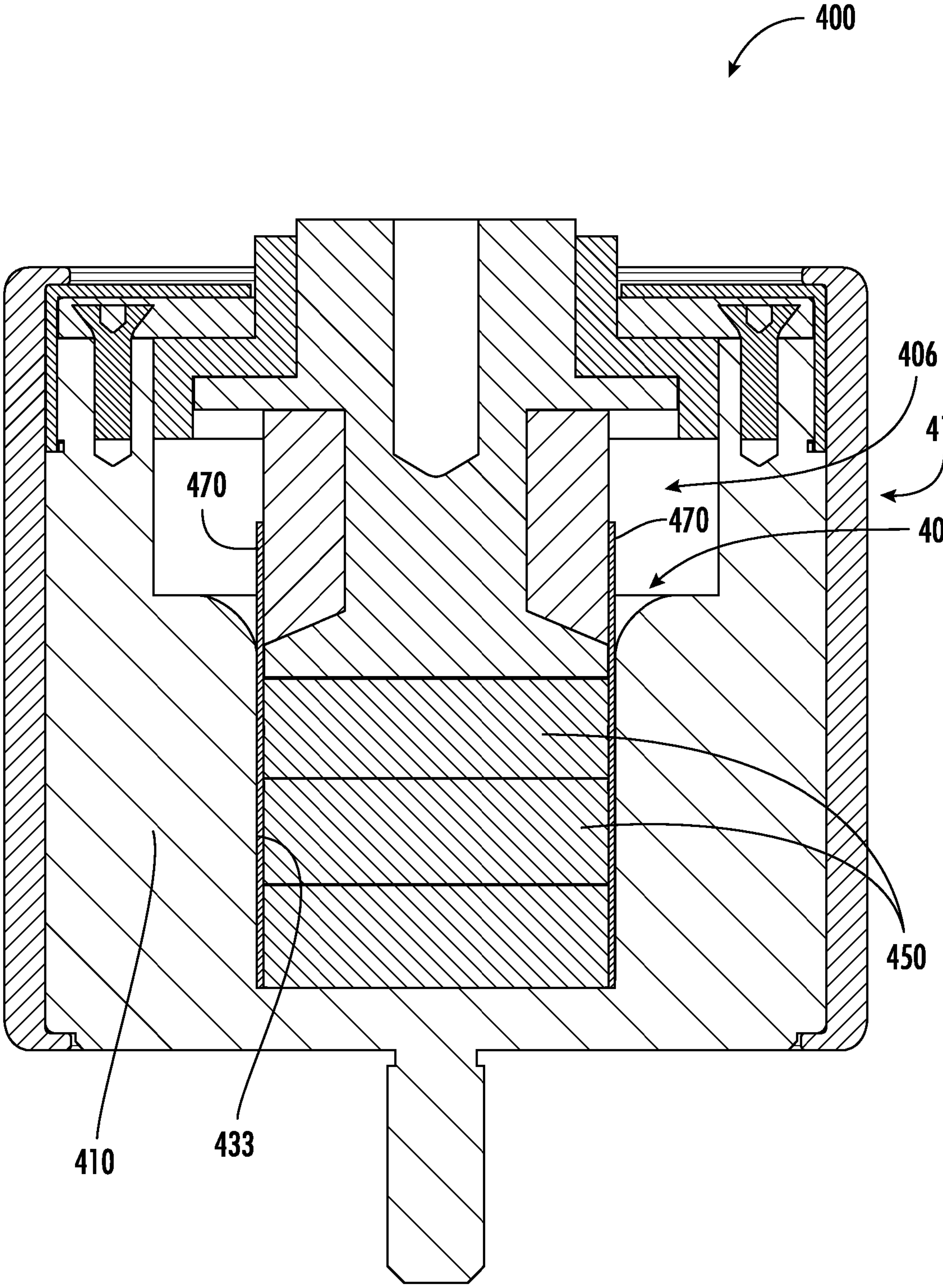
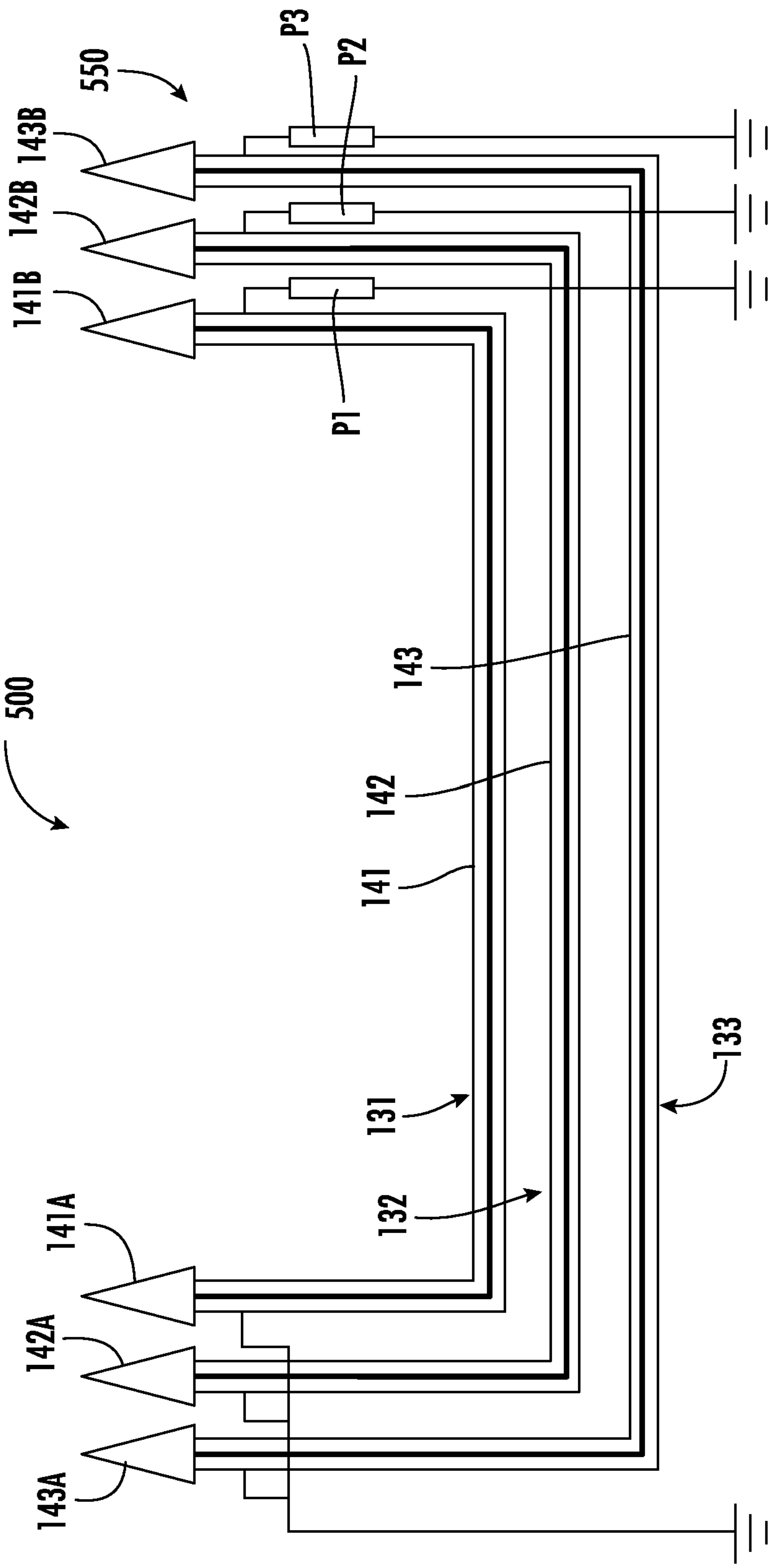


FIG. 17



500
550
P3
P2
P1
143B
142B
141B
141A
142A
143A
141
142
143
131
132
133

FIG. 18

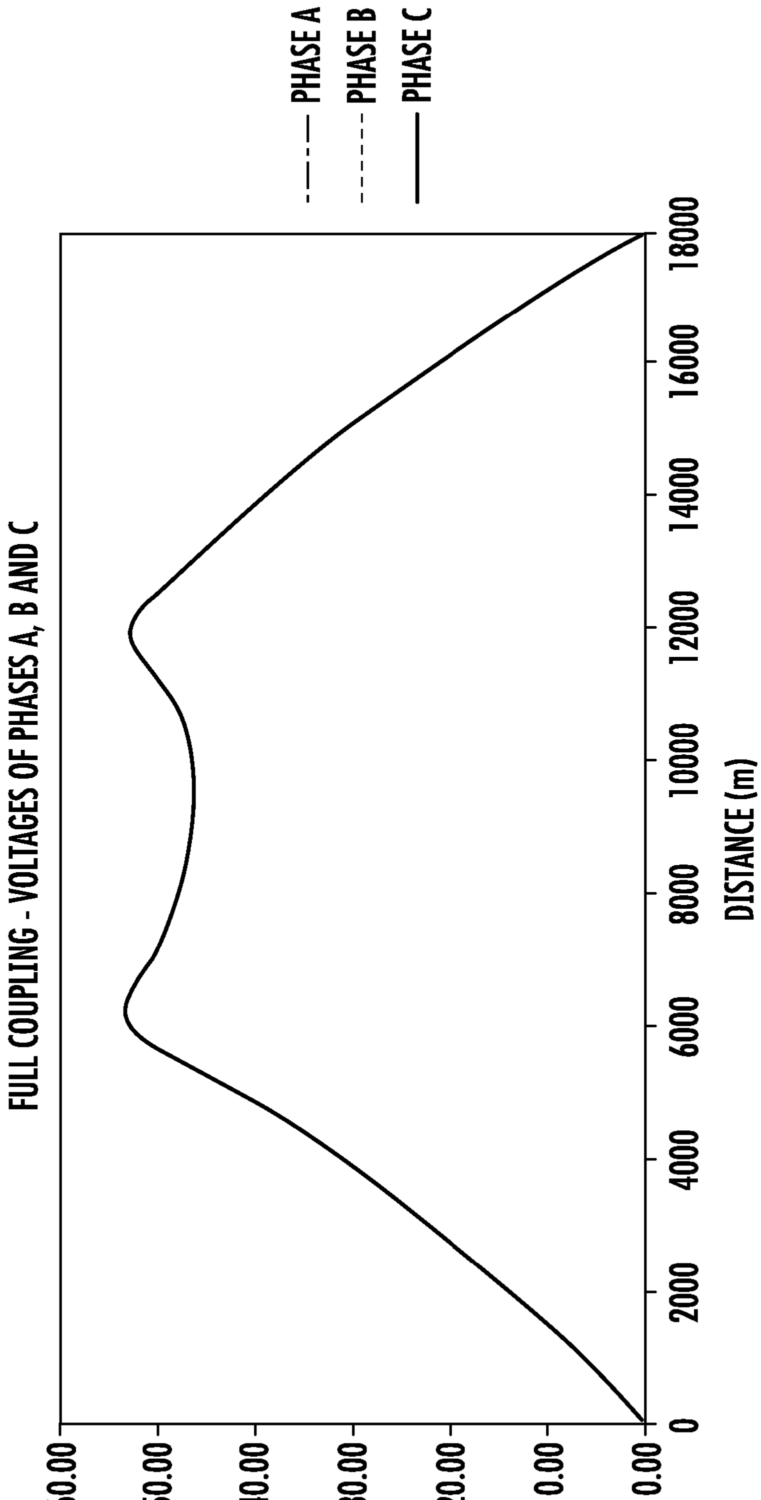

FULL COUPLING - VOLTAGES OF PHASES A, B AND C
PHASE A
PHASE B
PHASE C
VOLTAGE (Vrms)
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
DISTANCE (m)

FIG. 19

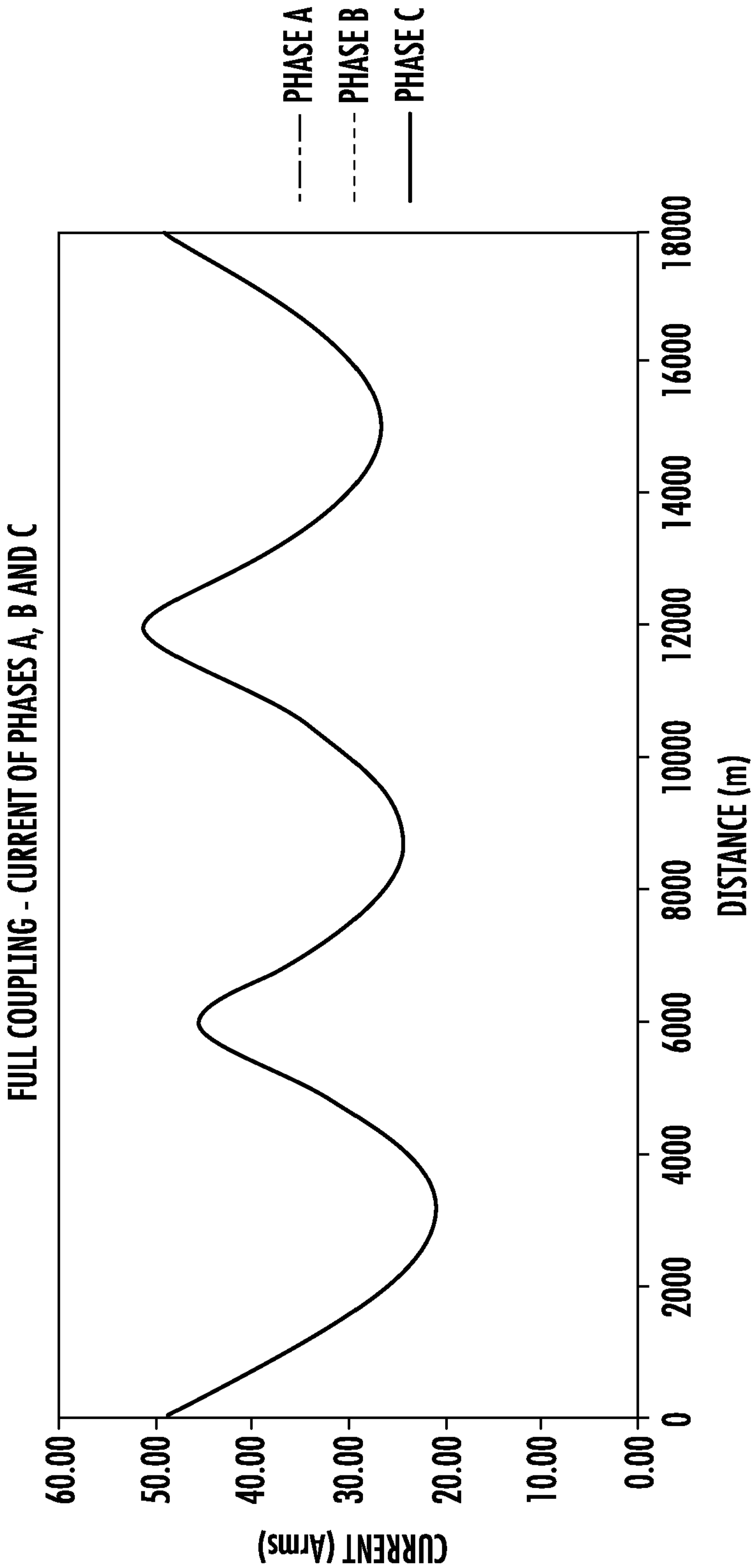

FULL COUPLING - CURRENT OF PHASES A, B AND C
CURRENT (Arms)
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
DISTANCE (m)
PHASE A
PHASE B
PHASE C

FIG. 20

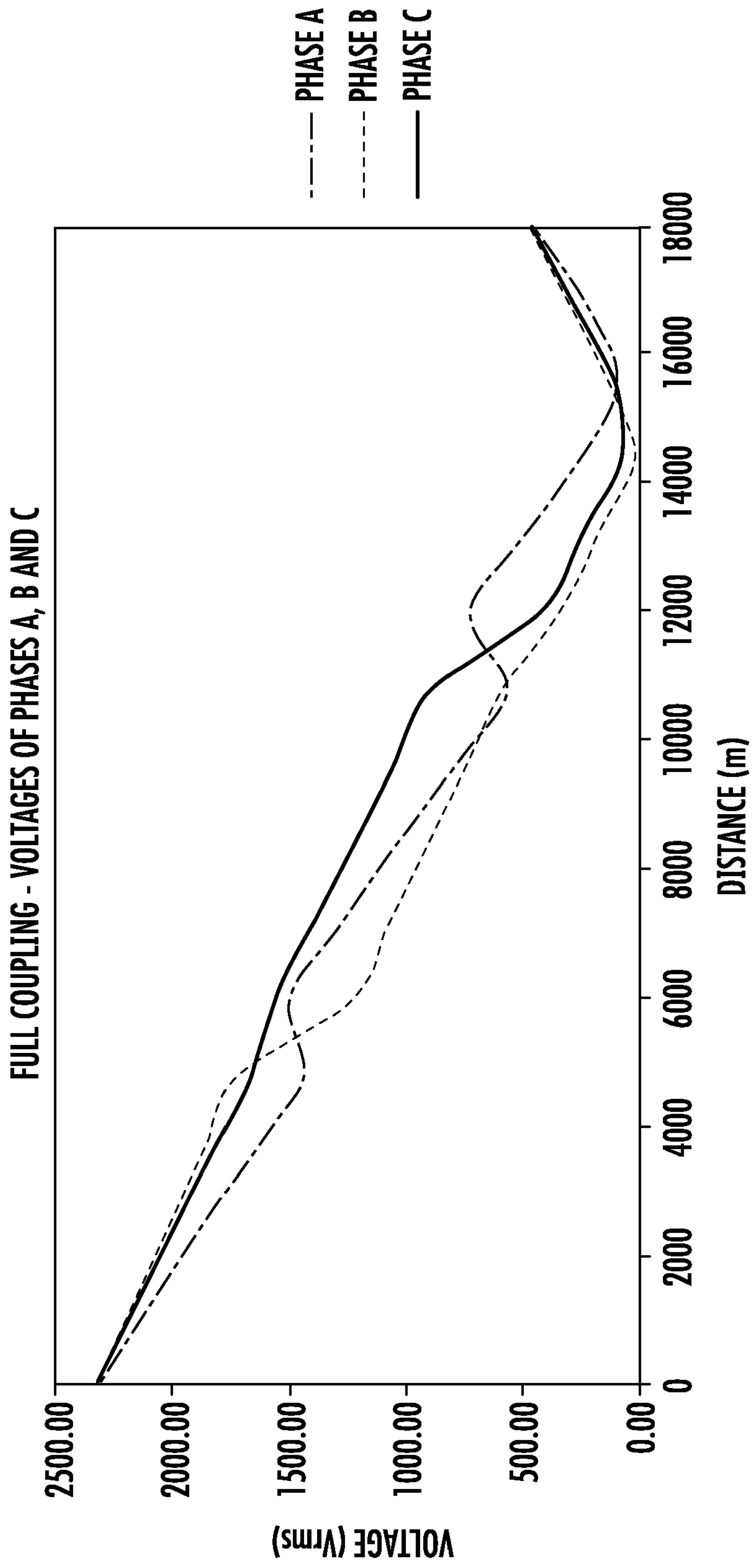

FULL COUPLING - VOLTAGES OF PHASES A, B AND C
PHASE A
PHASE B
PHASE C
VOLTAGE (Vrms)
2500.00
2000.00
1500.00
1000.00
500.00
0.00
DISTANCE (m)
0
2000
4000
6000
8000
10000
12000
14000
16000
18000

FIG. 21

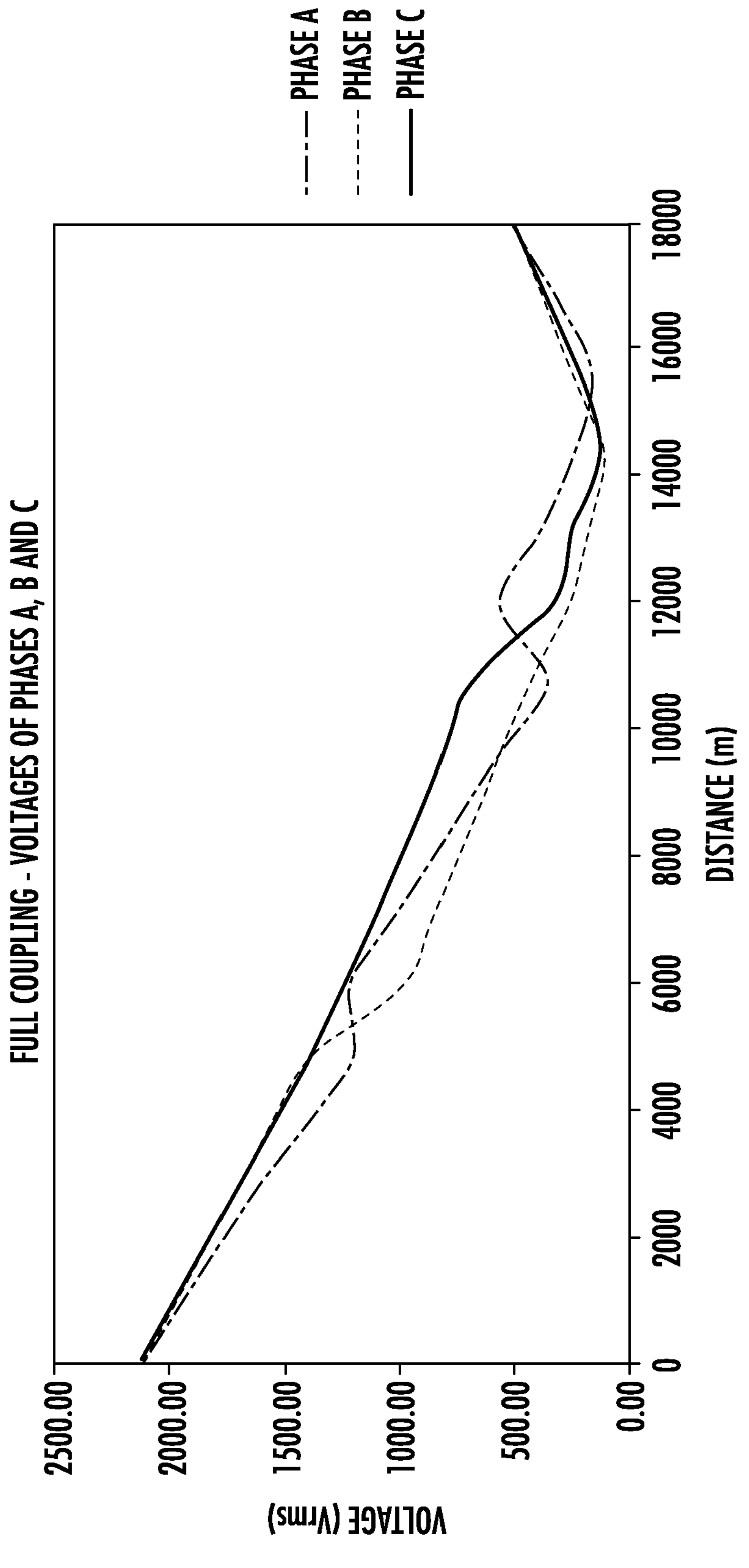

FULL COUPLING - VOLTAGES OF PHASES A, B AND C
PHASE A
PHASE B
PHASE C
VOLTAGE (Vrms)
2500.00
2000.00
1500.00
1000.00
500.00
0.00
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
DISTANCE (m)

FIG. 22

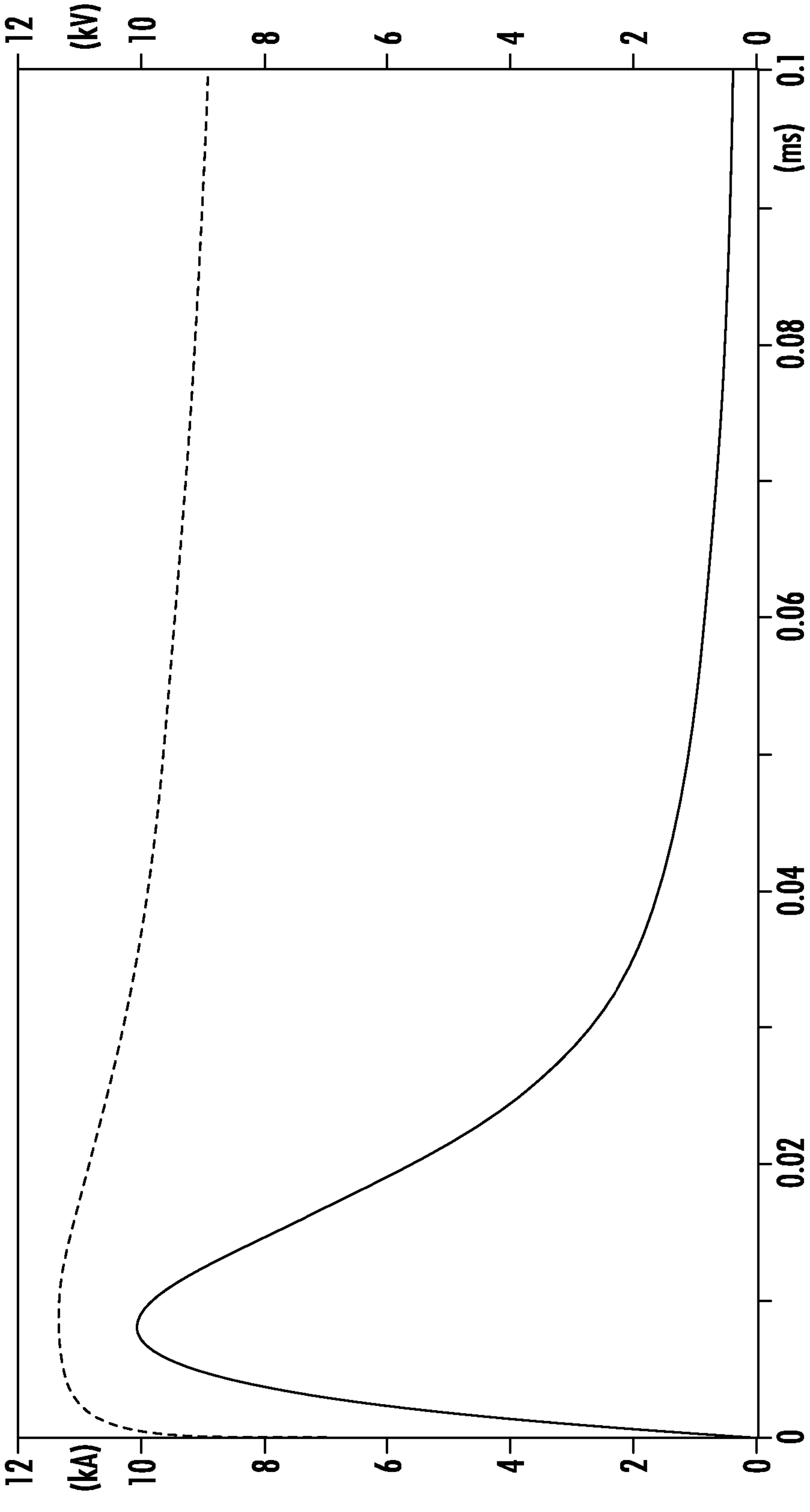


FIG. 23

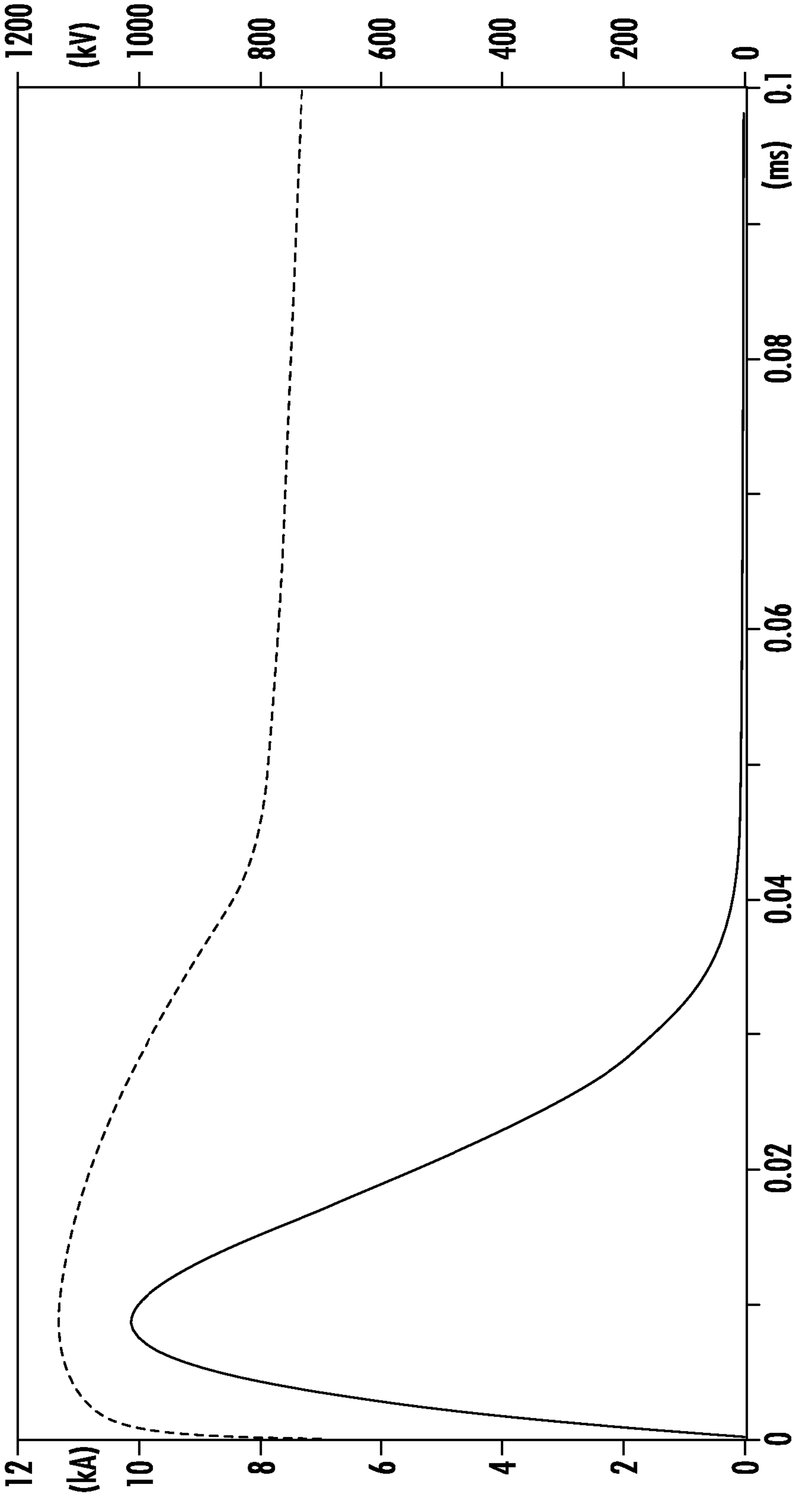

12
(kA)
10
8
6
4
2
0
1200
(kV)
1000
800
600
400
200
0
0
0.02
0.04
0.06
0.08
(ms)
0.1

FIG. 24

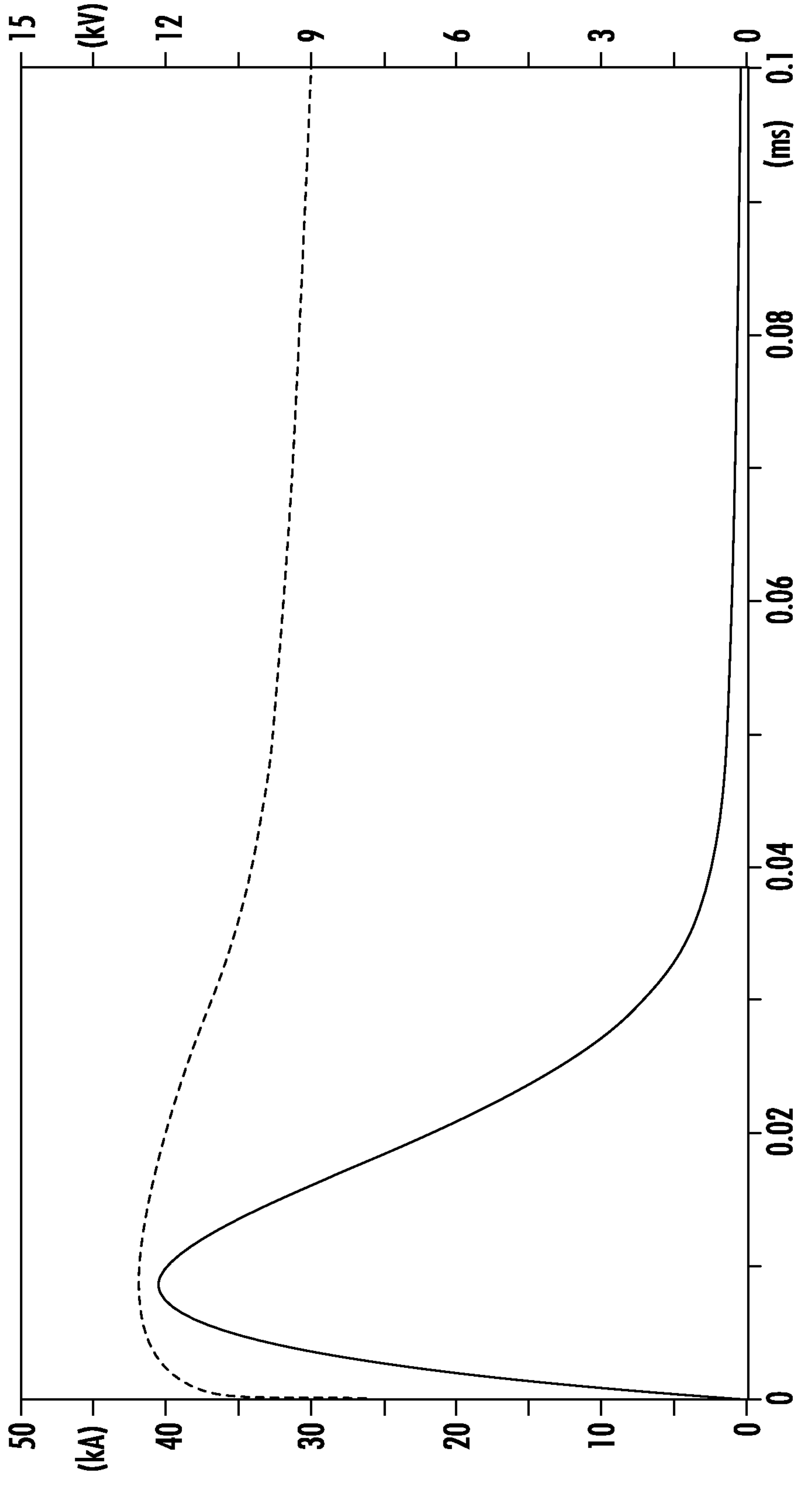


FIG. 25

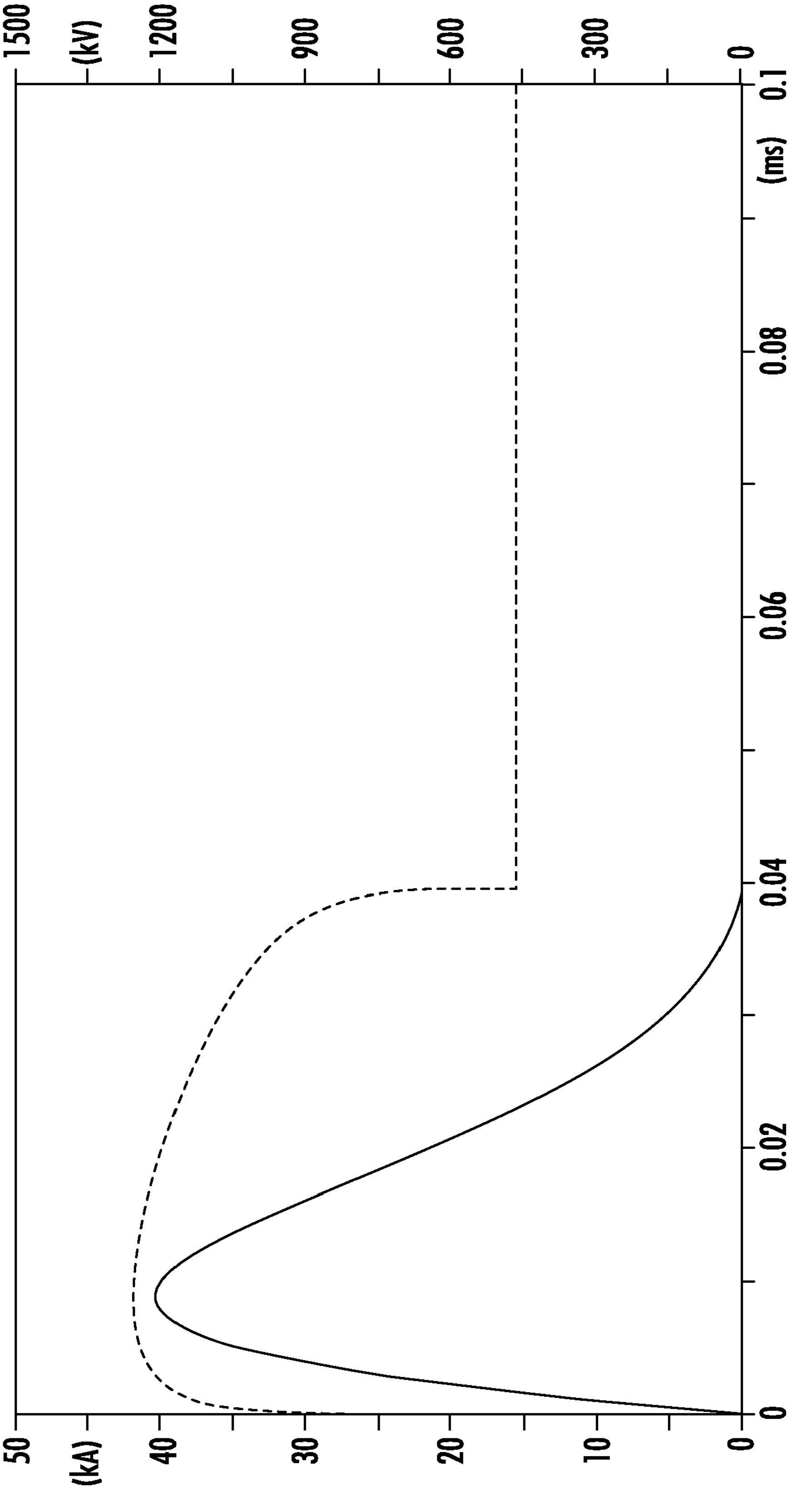

50
(kA)
40
30
20
10
0
1500
(kV)
1200
900
600
300
0
0
0.02
0.04
0.06
0.08
(ms)
0.1

FIG. 26

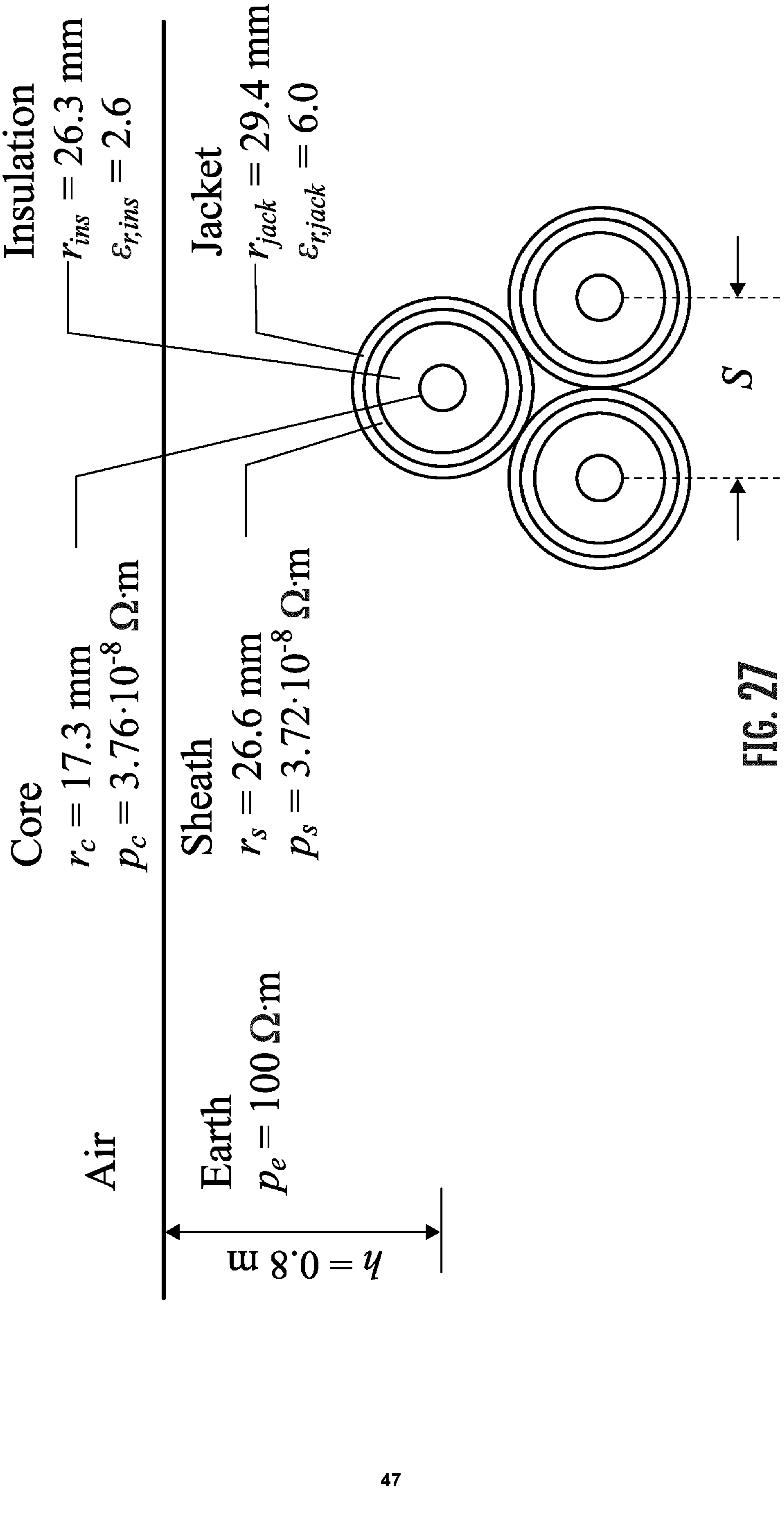

Insulation
$r_{ins} = 26.3$ mm
$\varepsilon_{r,ins} = 2.6$
Jacket
$r_{jack} = 29.4$ mm
$\varepsilon_{r,jack} = 6.0$
Core
$r_c = 17.3$ mm
$p_c = 3.76 \cdot 10^{-8}\ \Omega \cdot m$
Sheath
$r_s = 26.6$ mm
$p_s = 3.72 \cdot 10^{-8}\ \Omega \cdot m$
Air
Earth
$p_e = 100\ \Omega \cdot m$
$h = 0.8$ m
S

FIG. 27

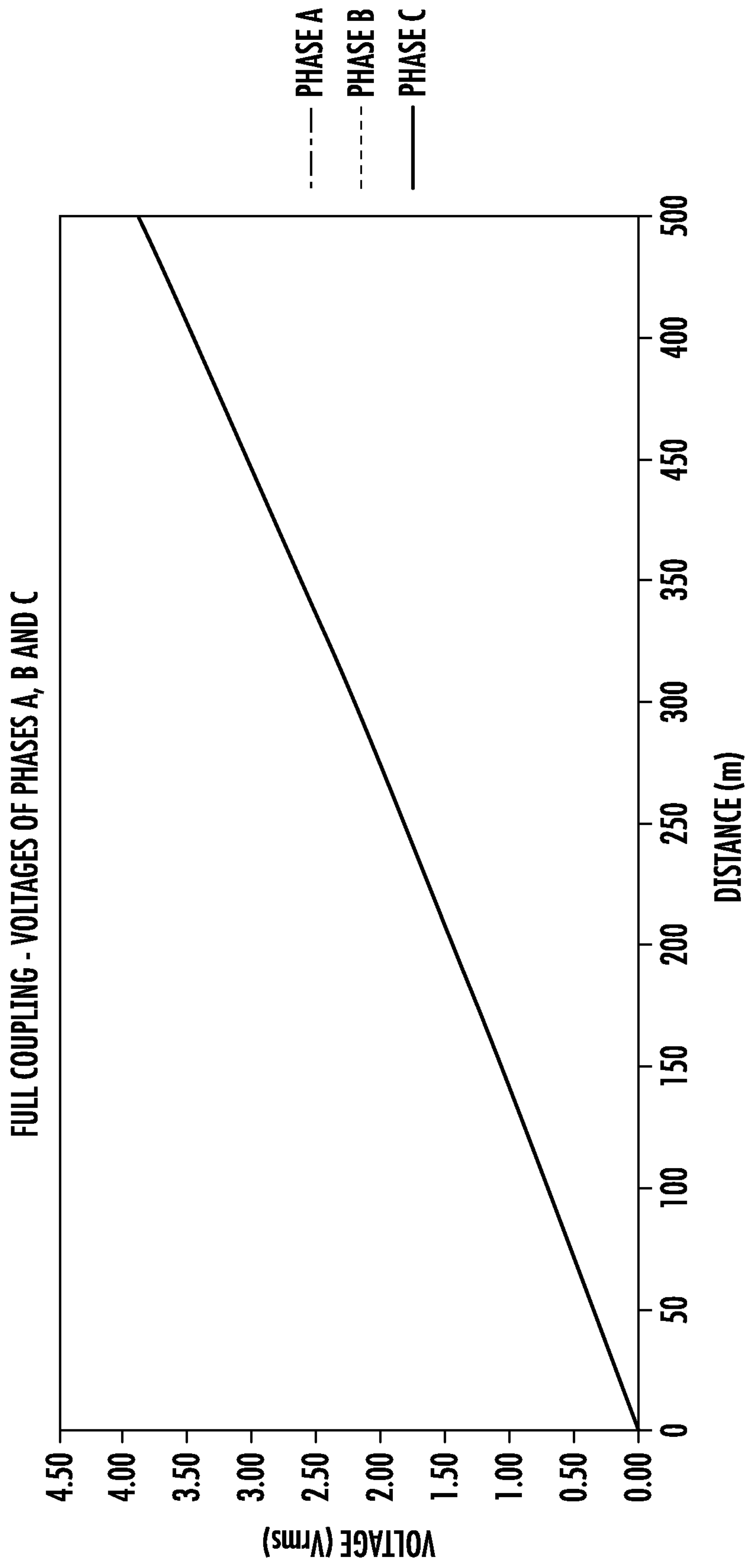

FULL COUPLING - VOLTAGES OF PHASES A, B AND C
VOLTAGE (Vrms)
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0
50
100
150
200
250
300
350
450
400
500
DISTANCE (m)
PHASE A
PHASE B
PHASE C

FIG. 28

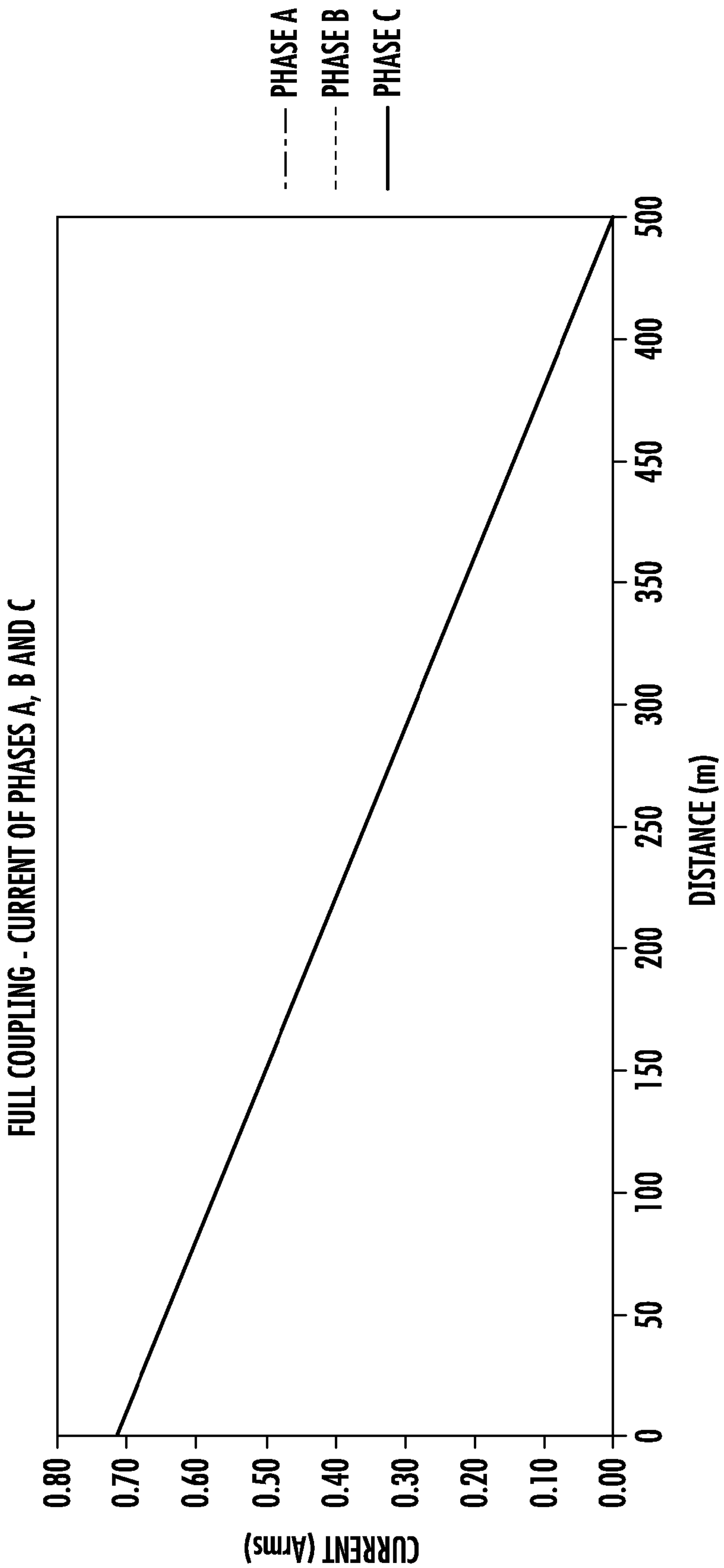

FULL COUPLING - CURRENT OF PHASES A, B AND C
PHASE A
PHASE B
PHASE C
CURRENT (Arms)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
50
100
150
200
250
300
350
400
450
500
DISTANCE (m)

FIG. 29

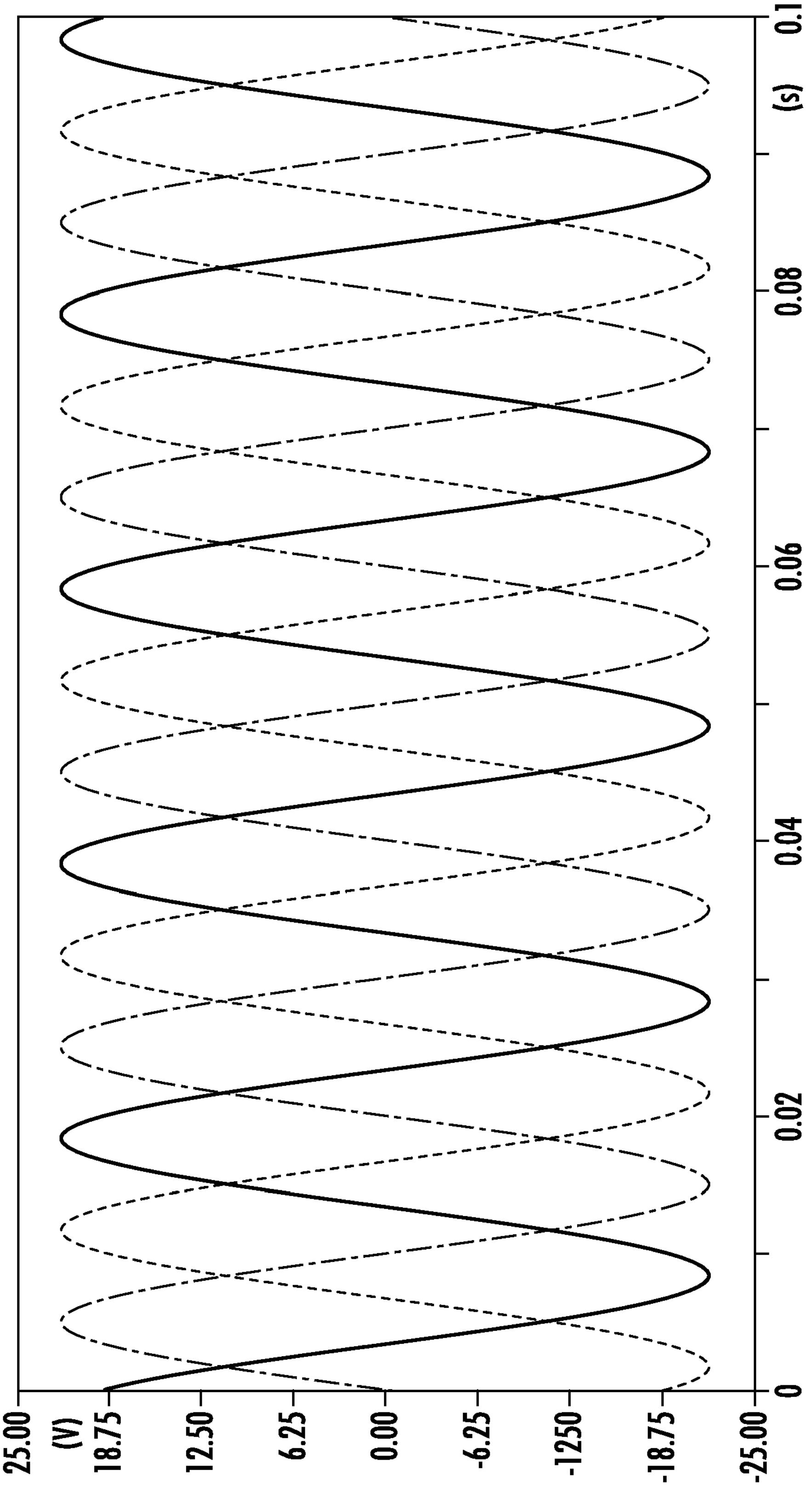

25.00
(V)
18.75
12.50
6.25
0.00
-6.25
-1250
-18.75
-25.00
0
0.02
0.04
0.06
0.08
0.1
(s)

FIG. 30

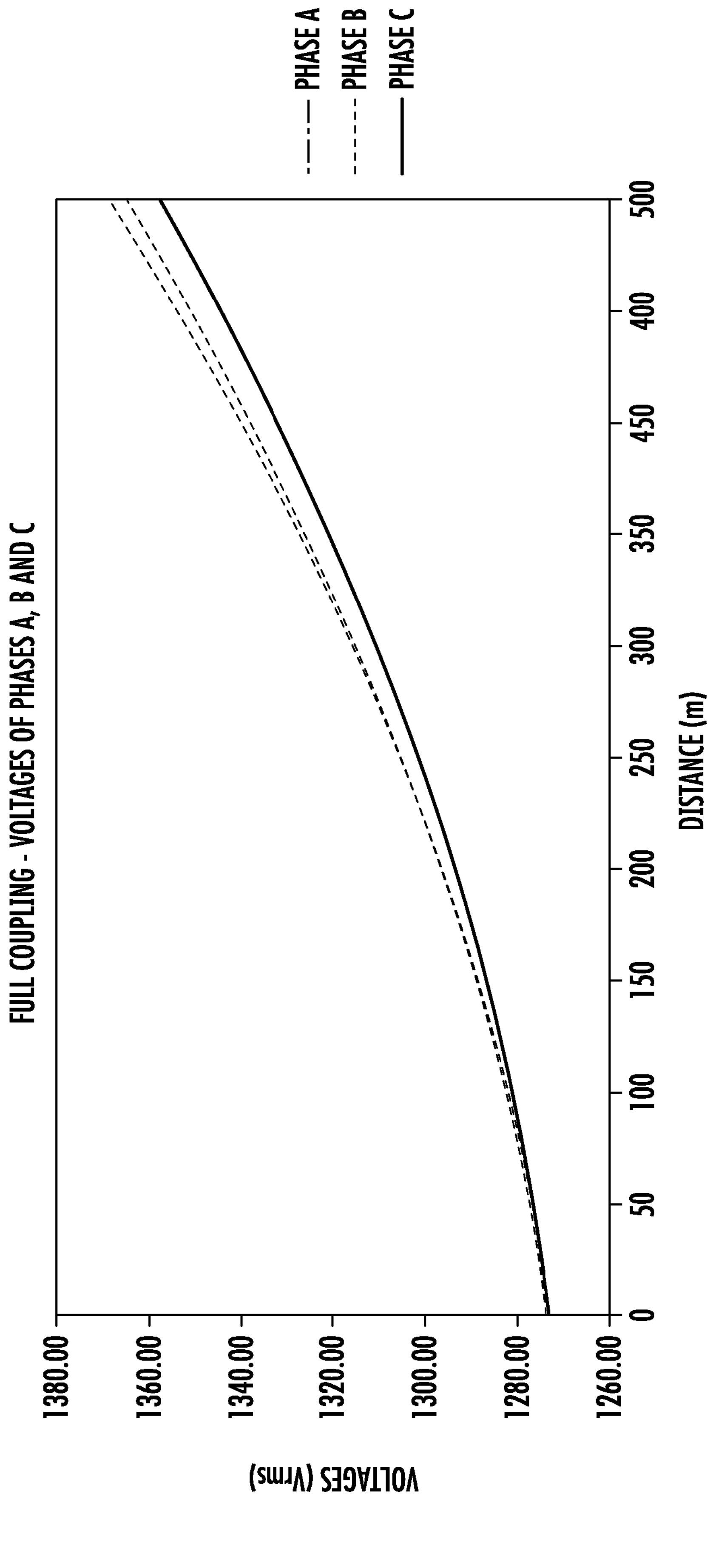

FULL COUPLING - VOLTAGES OF PHASES A, B AND C
PHASE A
PHASE B
PHASE C
VOLTAGES (Vrms)
1380.00
1360.00
1340.00
1320.00
1300.00
1280.00
1260.00
DISTANCE (m)
0
50
100
150
200
250
300
350
400
450
500

FIG. 31

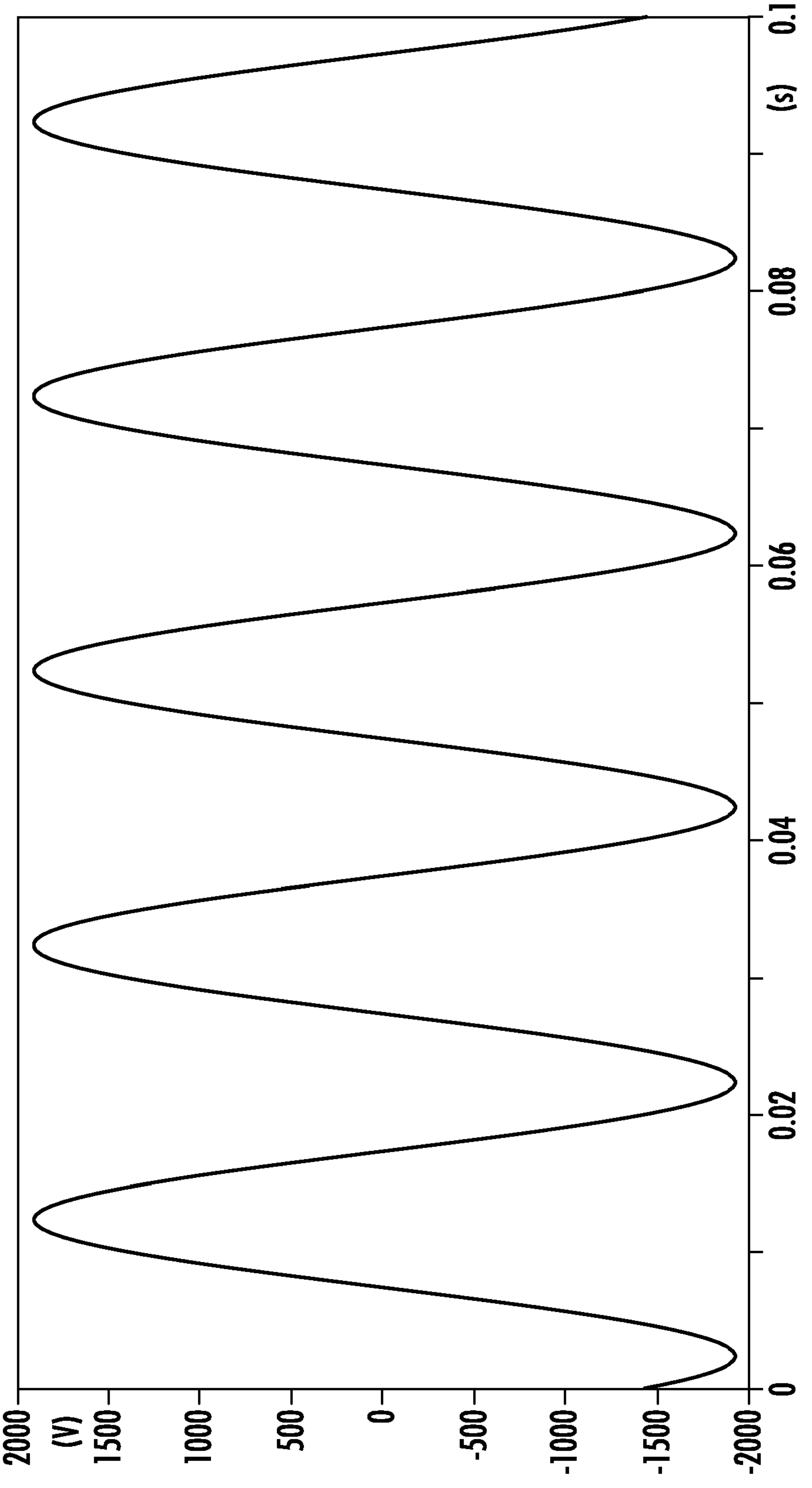


FIG. 32

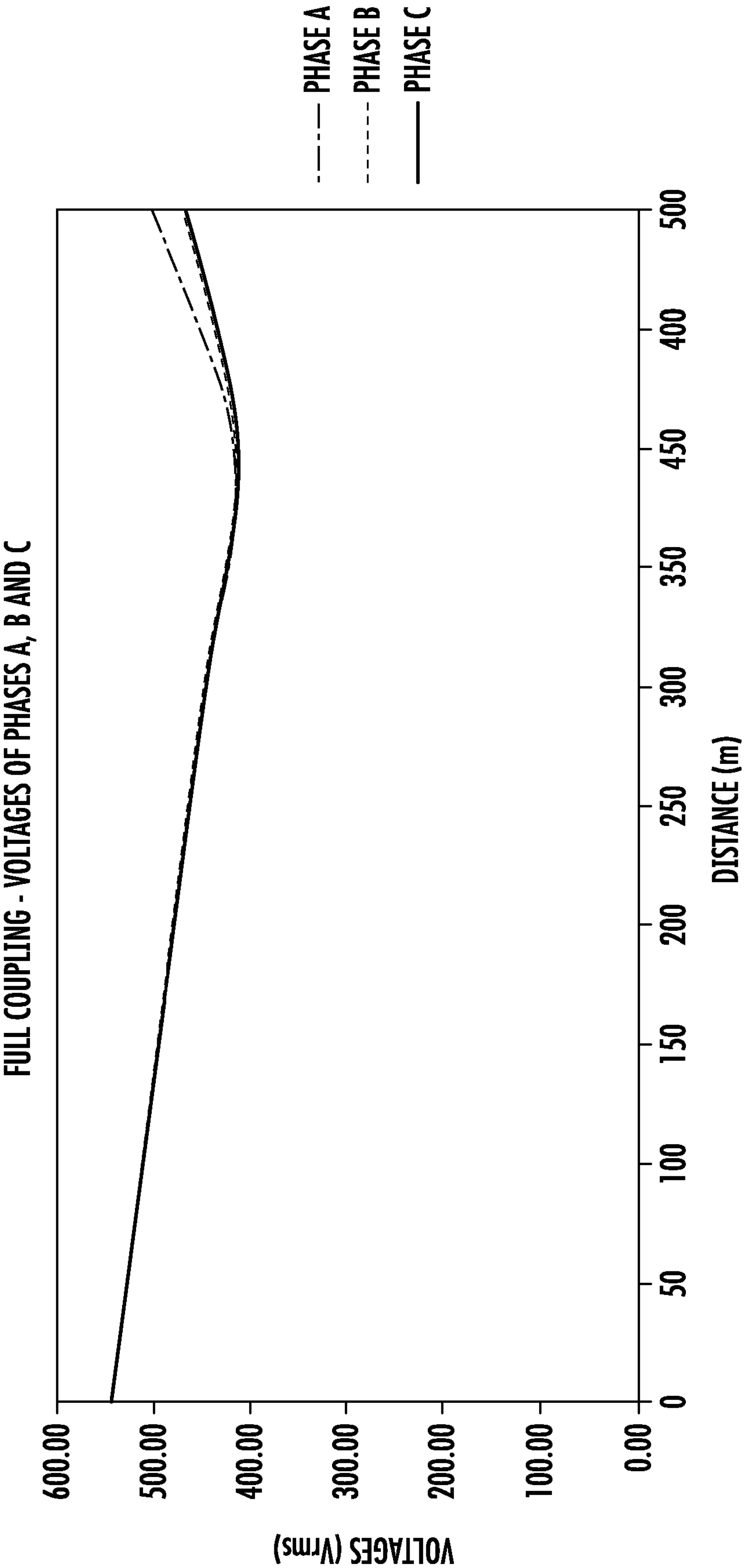

FULL COUPLING - VOLTAGES OF PHASES A, B AND C
PHASE A
PHASE B
PHASE C
VOLTAGES (Vrms)
600.00
500.00
400.00
300.00
200.00
100.00
0.00
0
50
100
150
200
250
300
350
450
400
500
DISTANCE (m)

FIG. 33

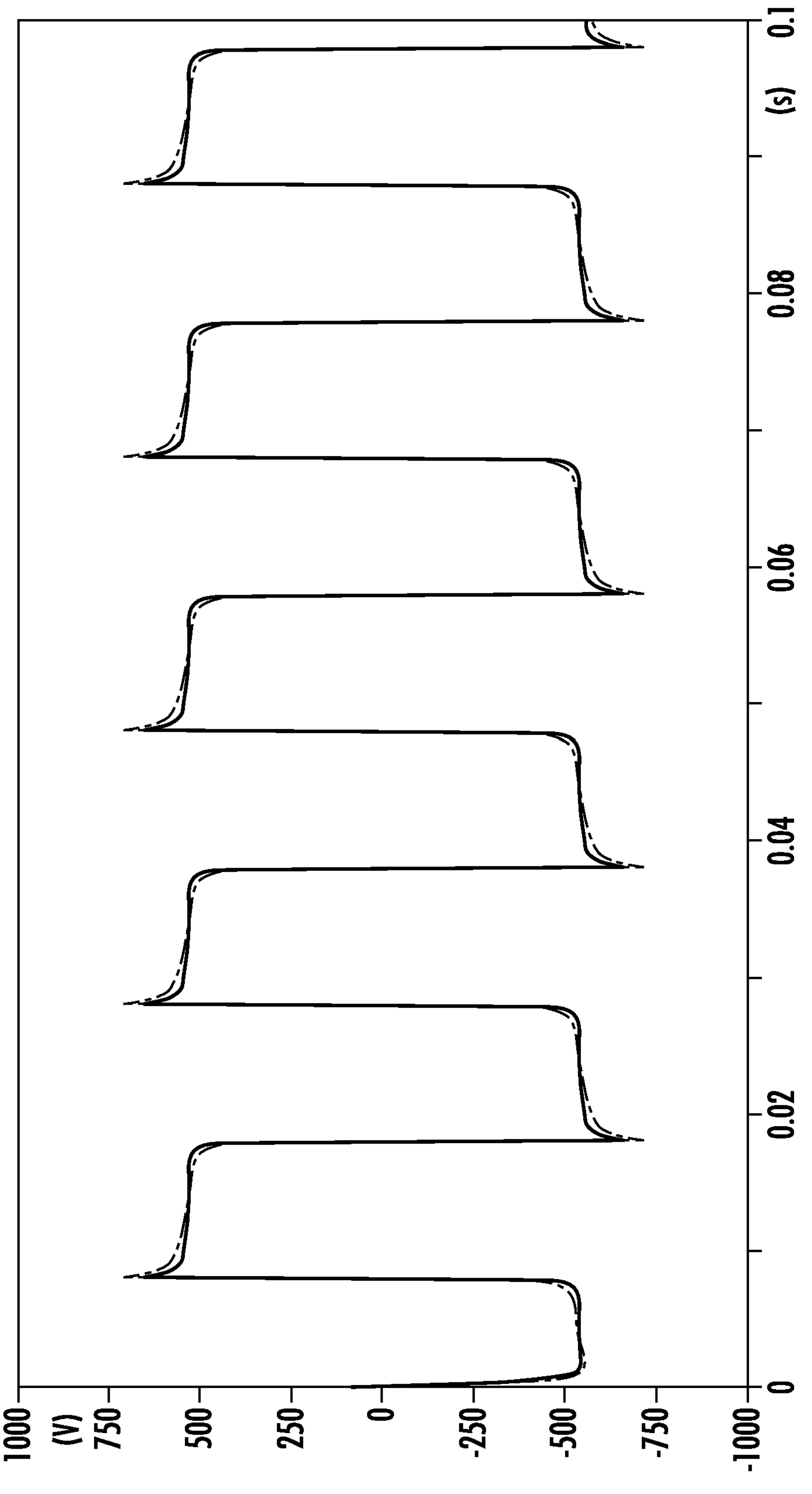


FIG. 34

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EUROPEAN SEARCH REPORT

Application Number
EP 24 20 3404

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	VLACHOKYRIAKOU OLGA ET AL: "A New Approach for Sheath Voltage Limiters in Medium Voltage systems", 2022 36TH INTERNATIONAL CONFERENCE ON LIGHTNING PROTECTION (ICLP), IEEE, 2 October 2022 (2022-10-02), pages 518-522, XP034227614, DOI: 10.1109/ICLP56858.2022.9942504 [retrieved on 2022-11-16] * abstract * * figures 1-2 * * paragraph [000I] - paragraph [000V] * -----	1-16	INV. H02H9/08 H02H9/00
A	JONATHAN WOODWORTH: "APPLIC ATION NOTE 3", IEEE DRAFT WGDS; 1328025400445, IEEE-SA IMEET CENTRAL, PISCATAWAY, NJ USA , vol. SPDC 4 October 2023 (2023-10-04), pages 1-14, XP068295429, Retrieved from the Internet: URL:https://ieee-sa.imeetcentral.com/p/aQAAAAAFEew_ [retrieved on 2023-10-10] * abstract * * figures 1-7 * * the whole document * -----	1-16	TECHNICAL FIELDS SEARCHED (IPC) H02H

-/--

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	24 March 2025	Operti, Antonio

CATEGORY OF CITED DOCUMENTS

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EUROPEAN SEARCH REPORT

Application Number
EP 24 20 3404

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	CARL MOLLER: "LINK BOXES", IEEE DRAFT WGDS; 861536632759, IEEE-SA IMEET CENTRAL, PISCATAWAY, NJ USA , vol. G6 4 June 2019 (2019-06-04), pages 1-12, XP068241681, Retrieved from the Internet: URL:https://ieee-sa.imeetcentral.com/p/aQAAAAAD318v [retrieved on 2023-07-11] * abstract * * page 4 - page 6 * -----	1-16	
			TECHNICAL FIELDS SEARCHED (IPC)

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